Robust Design Evolution and Impact of In-Cylinder Pressure Sensors to Combustion Control and Optimization: A Systems and Strategy Perspective.

by

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Abstract

In-Cylinder Pressure Sensors (ICPS) today are close to satisfying the robustness, performance and cost requirements for application to closed loop control and monitoring of production automotive engines. Using the Robust Design framework as a compass, this thesis first checks the evidence for emergence followed by tracking the evolution of the sensor component itself and its application to robust closed loop control of the combustion process in internal combustion engines.

After identifying the potential system level impact of the emerging ICPS technology, System Dynamic and Technology Strategy frameworks are used to find spillover triggers and to recommend a number of strategic options to generate and capture value for integrated system solution providers so that they can beat the very stable status quo that persists in the slow and mature prime mover industries.

In addition, Chapter 2 gives a data driven method for identifying the Skills needed for suppliers to realize the above recommendations. This method is based on collective intelligence of 690 experienced professionals with 20 years of work experience on average from 40 targeted companies, representing a large body of engineering and managerial experience in battling complex engineering system hurdles. This approach is more effective than blindly copying the prominent integrated system solution providers or OEM's, because a side effect of long term incremental innovation in the mature prime mover industry is that the underlying reasons for their success is ingrained in their "tacit knowledge" and "organizational furniture" and hence not explicitly understood.

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To my dear wife Ima: It took two years of struggling with an unusually heavy work load at Woodward and MIT and mum's losing battle with cancer, to discover that your love, understanding and support for me are the best examples of robust design that I know.

Acknowledgments

In completing this thesis, I confirmed that one can overcome difficult hurdles by tapping into a large pool of interdisciplinary enthusiasts. If you speak the right frequency and your intentions are good, enthusiasts resonate because this is in their nature. Here are some of the enthusiasts that deserve a particular mention:

Marek Wlodarczyk, inventor of the fiber optic sensor detailed in section 3.2.1, who patiently worked with me to bring me up the learning curve of subtle issues surrounding In-Cylinder Pressure Sensing.

Chad Foster for Design and Analysis of the Internet-Based Survey discussed in section 3.3.3 to understand the System Architectural Impact of the ICPS. Kelly Benson, Senior Staff Engineer at Woodward for helping distribute the survey of section 3.3.3 among engine professionals.

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Last but not least: Don Clausing and Dan Frey for spreading Robust Design, because this philosophy is the only well developed compass that guides the path to solving a wide spectrum of Socio-Technical complex system issues with limited resources.

Contents

List of Figures

Chapter 1

Introduction

> ”Prediction is very difficult, especially if it’s about the future”.
>
> –Nils Bohr, Nobel laureate in Physics

In-Cylinder Pressure Sensors (ICPS) have been widely used to improve the efficiency and emissions of internal combustion engines. Due to their cost and reliability problems, these sensors were not applicable to closed loop control of the combustion process in production engines. Their use was typically limited to laboratory, calibration or development configurations. Today, these sensors are close to achieving the ideal requirement of 98 % accuracy within the temperature range -40^oC to 250^oC, 5 billion Cycles at a cost of \$5 per sensor. If recent detailed announcements by Audi, Honda, VW and GM are genuine, then the application of these sensors to combustion control on production engines is imminent.

1.1 Outline of Thesis

This thesis has three main parts. Chapter 2 explains why the Robust Design Philosophy is used as a compass for dealing with the emergence of the ICPS. It starts with a brief background by citing from published sources that includes the author’s personal experience. This is followed by correlations and hard evidence for links between Robust Design and the biggest systems engineering hurdles that complex engineering system OEM’s face today, based on real data and not opinion. There is strong support for Robust Design from excellent reputable sources. However these are usually limited to one or few people's experiences and not based on experiences of a large pool of experienced systems professionals. Furthermore there are no reference on how Robust Design ranks when compared to other frameworks. Here the author collected a very rich set of data (690 experienced engineering systems professionals from 40 targeted companies) using a survey of companies working on complex engineerings systems in Colorado to discover how Robust Design correlates to other competencies and hurdles faced by companies in practice.

Chapter 3 focuses on the Robust Design Evolution of the architecture of the In-Cylinder Pressure Sensor (ICPS) as well as the architectural impact on Engine Systems, by examining patent literature and interviewing a number of R&D people that have influenced the evolution of the sensor and its application in combustion control systems. This part covers various types of ICPS sensing elements, their integration with other components inside the cylinder and a number of leading products that are currently available on the market. This chapter also deals with understanding the detailed systems impact of ICPS technology to Robust Control of Combustion in production engines. This is very challenging due to the intense competition between engine OEMs. Nevertheless, the thesis sheds some light on the systems impact of these sensors by analyzing information in the open literature and a purpose made survey that was sent to engine professionals working on either the technical or commercial aspect of engine development.

Chapter 4 focuses on the dynamics of the ICPS technology adoption in the automotive market, spillover into the similar Power Generation market, and technology strategy recommendations for integrated system solution providers who want to capture more of the pie in the slow mature prime mover industry.

There is a list of conclusions at the end of each chapter. But here is a couple of bottom line take away conclusions that this thesis supports:

- *The key to ensuring success in mature prime mover industries is the explicit understanding of how to generate and capture the cost effective robust performance value that emerges* *from the interaction of simpler socio-technical elements.*

- *An opportunity to learn from failures, or a good way to avoid them, is to gain structural understanding of the dynamic causal loop relationship between the above value and the value measured in dollars.*

This thesis applies the following key approaches taught in the Systems Design and Management Program at MIT:

- Robust Design Frameworks[16, 17, 18, 19, 15]
- Extraction of Information from Distributed Intelligence (Interviews and Surveys)
- System Dynamics for Business Policy[1, 2]
- Theory of Inventive Problem Solving (TRIZ): Laws of Evolution of Technological Systems[16]
- Technology Strategy Frameworks[14, 20, 21, 13, 22, 23]

The remaining sections of this chapter provide the basic background to the emergence of the ICPS Technology .

1.2 Emergence of the ICPS Technology

How do we know that the ICPS technology is indeed emerging? Note that emergence does not necessarily imply market dominance over another technology although that is one of the eventual possibilities with emergence. In this section we merely present enough evidence to convince the reader of this emergence. This section is necessary because a significant number reputable engine professionals or researches still believe that ”it will never work” or that ”you will never see this in production” possibly due to the long time that has passed since the first ICPS concepts tried to emerge unsuccessfully in the late 80’s and early 90’s.

Another possible reason for the skepticism is the issue of tacit knowledge. For example, an excellent performance engineer may not see enough steady state performance advantage to justify an architectural change. But the advantage may be in the combination of performance plus simplification or robustness of the architecture plus better dynamic performance and shorter time to market. In complex engineering systems then, the overall correct conclusion that emerges may be very different to those of individual experts who no doubt understand their domain deeply.

1.2.1 The *Dominant Design* in Combustion Control

There is a huge amount of literature in the form of papers, books and patents on sensing the combustion process in internal combustion engines dating back to the 1980's. There is a clear split between supporters of the ICPS and supporters of alternative sensors chief among which is the Ion Sensor. For example, on the one hand, Leonhardt et. al.[24] expected that cost effective durable real time ICPS:

> "offers several advantages over conventional control strategies: improved engine supervision; improved performance and greater fuel economy; improved driveability; reduced sensitivity to engine component manufacturing tolerances; ability to adapt to engine wear and aging, as well as to changing environmental conditions and to variations in fuel quality; emission reduction; less calibration expense."

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While on the other hand, Gazis et. al. [25], in 2006, still question the high cost and long term performance of the ICPS and state that:

> "pressure sensors are used for research purposes, a target to be met rather than a solution in themselves."

They propose using ion sensors that are well correlated to the features of the pressure signal inside the cylinder such as the peak pressure cylinder position and magnitude. Despite the range of opinions, one can detect an overwhelming agreement among all camps. In the words of Guzzella and Onder[11]:

> ”The pressure of the gases in the cylinder provide the most direct signal available for engine control purposes. Since the interpretation of this variable is a well known tool in ICE research and development, numerous control algorithms based on that information have been proposed.”

Indeed, the Engine Control literature confirms that, right or wrong, the *Dominant Design* in closed loop engine control algorithms appears to be based on the cylinder pressure variable that may come from ICPS or from another sensor or estimator that is correlated to it. The concept of dominant design is very key here. Utterback [26] tracked the dynamic evolution of several new technologies and introduced the concept of dominant design. He found that, once a dominant design is reached, it tends to stay dominant for a relatively long time making it very hard for alternatives to disrupt or survive. *Dominant Design* has some key advantages. For example, we can get into almost any new car without specific instructions on how to operate it. This evolution pattern explains why for example most laptops, cars, and bicycles have very similar high level architecture. Clausing and Fey [16] track the evolution of the bicycle and show that its basic architecture and familiar appearance was unchanged since the invention of the free-wheeling clutch. There will have to be a very strong driver or disruption for anything other than the QWERTY computer keyboard to emerge despite the fact that it may not be the most ergonomic or logical design or superior design. By analogy, whether ICPS sensors are used, or whether an alternative or virtual sensor is used that correlates to it, it appears that the *Dominant Design in understanding and controlling the combustion process is via the cylinder pressure variable.*

1.2.2 Recent Announcements by Audi, Honda and GM

One needs to be very careful interpreting announcements from engine OEM’s. In an interview, a colleague at MIT commented that sometimes OEM’s announce a new technology that will never appear and at other times, no announcements are made and yet suddenly several OEM’s roll out a new technology within a very short period. He gave the Piezoelectric fuel injection valves as an example. This point is well taken. The dominant logic being the elements of surprise in a very competitive market.

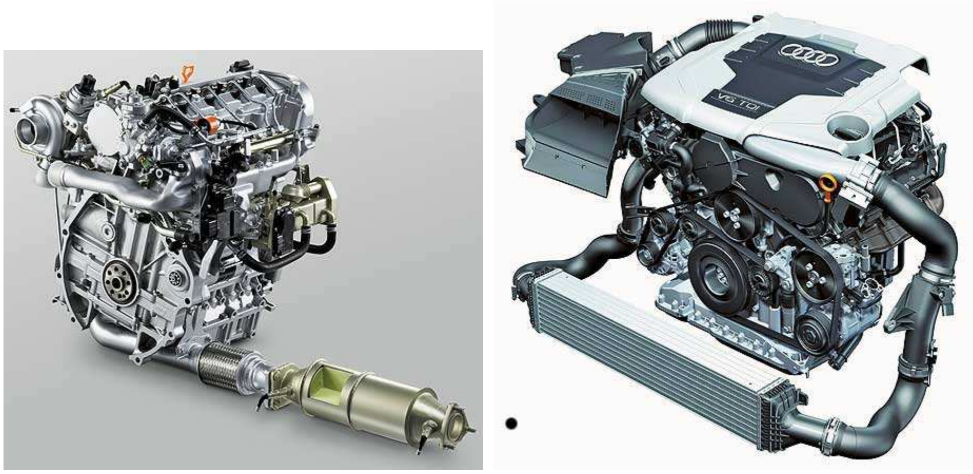

Figure 1-1: The Honda iDTEC Engine [3] and The Audi 3.0 L TDI [4] pictured in SAE Automotive International Magazine.

Soon thereafter, The SAE Automotive International reported on Audi's next generation 3.0L TDI engine [4] shown in figure 1-1 that will be installed by mid-2008 on production Q7 followed by the A4 with Bin5, Euro 6 emission levels. Here is an excerpt form the article:

> "... It was Volkswagen's new, high-pressure common-rail 3.0-L TDI with integrated cylinder pressure control and AdBlue exhaust after-treatment technology. Due in production this year, the engine not only produces 176 kW (236 hp) and 500 Nm (369 lbft), but is also claimed to be the cleanest diesel in the world, with exhaust emissions projected at EU6 levels...An essential element of its ultra-low-emissions system is its exhaust after-treatment system with AdBlue, which will play a major part in achieving Audi's target to cut NOx by up to 90 % to about 0.017 g/km (0.027 g/mi) ... One of the highlights of the new engine is the use of combustion chamber sensors that enable more precise regulation of the combustion processes. This is the first time that such sensors have been fitted on any engine in the world, claims Audi. No CO2 figure has been released for the engine, but it is understood that Audi may try to raise the injection pressure even further, which would bring

> potential CO2 and fuel consumption benefits. ”

SAE Automotive international also reported on the Honda iDTEC engine [3] shown in figure 1-1 as follows:

> ”Not long after you read this, a diesel-powered Honda passenger vehicle will enter the U.S. EPA’s Mobile Emissions testing facility to begin its certification process for the 2009 model year...CEO Takeo Fukui, his chief of R&D, Hirohide Ikeno, and the young diesel engineers AEI spoke with at Honda’s Motegi proving ground and Tokyo Motor Show last October are clearly proud of challenging Europe’s best in the compression-ignition arena...To meet EPA Tier 2 Bin 5 regulations, currently the world’s most stringent automotive emissions standards, and with an eye toward the even tougher California SULEV (super ultra low emission vehicle) standards (the equivalent of EPA Bin 2), Honda diesel engineers focused on reducing engine-out emissions through advanced combustion control, coupled with unique after-treatment technology. Therefore, i-DTEC will feature a premixed-charge combustion process known as PCCI. This is a diesel variation of homogeneous-charge compression ignition (HCCI) in gasoline engines. Both processes require monitoring and feedback of individual cylinder pressure for optimum operation.”

GM also announced the Cadillac CTS for 2009 production [27] and plan for the Opel Vectra [28] where ICPS is specifically mentioned.

Now, all the above announcements are very specific and very near term.

1.2.3 Growth of ICPS Patents

Clausing and Fey [16] give a very rigorous framework and process for analyzing the evolution of new versus established technologies. By evaluating patents in a particular way and linking them to what they call the ”Laws of Evolution of Technological Systems their framework helps to identify new strategic opportunities or pick winning technologies.

Since we are only after showing emergence, a very rudimentary version of their patent analysis approach is shown in figure 1-2. The plot compares the growth with of the cumulative number of In-Cylinder Pressure-Based (in blue diamond) versus the total cumulative number of combustion control patents (in pink squares). We clearly see that combustion control patents grew very rapidly starting in the mid 1990s but appear to be stabilizing since 2003.

The secondary vertical axis shows the growth of the share of the ICPS (yellow triangles) as a percentage of the total number of combustion control patents. Here we also clearly see the exponential growth in the share of the ICPS based patents since 1990. Note the sudden short lived excitement around 1985.

The patents were searched using Google Patents using the search criteria:
engine combustion-control -turbine
and *engine combustion-control in-cylinder-pressure OR combustion-pressure -turbine*
from Jan 1776 to Dec 31 of each year plotted. The term 'turbine' was used to exclude turbine engine combustion control from internal combustion engine. The search option for all Patents filed was selected versus just the patents issued.

Again, Clausing and Fey give a much more reliable and rigorous method for evaluating and ranking patents but the reader will confirm that the cumulative patent curves presented look at least like an emergence.

1.2.4 Conclusion on Emergence of ICPS

This above arguments gave clear evidence that the In-Cylinder Pressure Signal is the Dominant Design for probing the combustion process. Any other method of sensing, such as virtual sensors via observers will have to be verified and validated by correlating to this defacto standard.

Furthermore, it is very hard to disregard the announcements by Honda, Audi and GM, because they give very detailed production dates in 2008 and 2009 and precise model details and emission numbers. The Honda announcement in particular is very valuable because they have an excellent reputation for robust performance at reasonable cost and these are the biggest complaints of those opposing the ICPS.

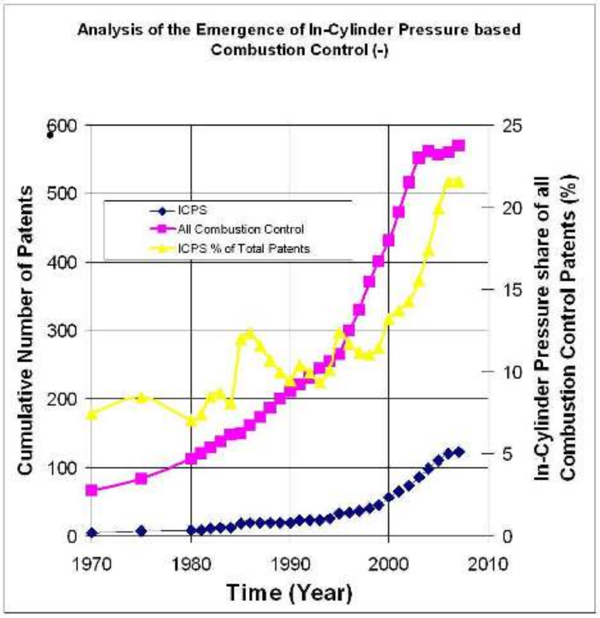

Figure 1-2: Growth in the Number of ICPS related and Combustion Patents.

A rudimentary plot of relevant patents also showed emergence.

Now each of the separate pieces of evidence above is not absolutely watertight when considered separately. For example Honda, GM and Audi may be competing for the "buzz" factor or purposely trying to confuse their competition or continually "testing" the market. However, when we put all the above pieces of evidence together, we see that the next stronger evidence is when these cars are parked in our drive way.

1.2.5 Why is the emergence of ICPS a Systems Issue?

Systems impact of new technologies was an item to be rated in the general Colorado Survey in Chapter 2 that compares this to other system type hurdles that mature complex engineering system developers face in general. This item was also rated in the engine world specific survey in Chapter 3. It is a system issue because the emerging ICPS technology fits in the category of architectural innovation. Using Rebecca Henderson's [14] framework for analyzing innovations, the emergence of ICPS falls into the *Architectural Innovation* category. In other words, it is not just a drop in replacement for another component. Here the core system ideal of combustion control is not changed but the relationship between combustion control and the system components change drastically. To begin with, ICPS has the potential to replace knock , misfire detection, mass air flow (MAF) and manifold pressure (MAP) and cylinder balancing subsystems. In addition, the combustion process that was previously regarded as noise is now being directly sensed and controlled via fuel injectors.

Since the architecture changes the robustness properties that is first and foremost dictated by the architecture also changes. The ripple effects of this change on the system are significant, so much so that the business model of OEM's and their suppliers get affected.

Chapter 4 focuses on exploring this topic to see how component suppliers can move up the food chain to capture more value as an integrated systems supplier. In both the power generation and automotive markets, the engine OEM's business model (i.e. profits) relies on continually pushing down the component prices while holding on to the value generated by System Integration. For example, a combustion control component supplier told the author that a particular component may start selling at \$12/unit but this is eventually pushed to \$2/unit in a matter of 5 to 10 years. Patenting is not effective against this price squeeze since the market and pace of technology is typically very slow. For example in the fast High Tech industry, very different to the automotive world, the inability to copy or find a way around a patent for only a couple of years means that the Patent is in practice a very effective barrier. Even if Patents were very effective, sustaining a predictable cycle of innovation to always have a superior component offering is not only difficult but it fails since the slow industry goes through relatively very few architectural changes with time.

Another problem is that OEM's typically can push the component supplier with new technology for exclusivity for say 5 to 10 years. Here the component supplier will be unable to dominate the market for that component while other players are fast catching up to provide an alternative solution. Hence the only way to capture more value is by becoming an integrated systems solution provider to the OEM's but this is precisely what the OEM's business model itself is based on: i.e. the profits come from capturing value by being the system integrator while squeezing the cost out of components. Hence, for component suppliers, moving up the food chain to become an integrated system supplier to resolve this dilemma is very challenging. This a very interesting systems and business problem that deserves attention.

Chapter 2

The Robust Design Compass

"Intellectuals solve problems, geniuses prevent them.".

–Albert Einstein

This witty quote fits extremely well with the main aims of Robust Design. Given that in the domain of mature complex engineering systems (e.g. automobiles, aircraft, spacecraft, power generation systems) we will never be permitted to deliver complex engineering systems that are unreliable, the question is where do we attack first or which fight to we pick if we had this ideal choice. Do we want to solve problems that we detect during Verification and Validation Tests[1] or do we want to prevent them from occurring in the first place. If, we care about maximizing profits or minimizing the time to market, then the answer is already given in countless design or systems references such as the INCOSE Systems Engineering Handbook [29] or Effective Innovation by Clausing[16]:

- *It is factors cheaper and easier to prevent problems upfront rather than what Clausing calls frequent Build-Test-Fix Cycles at the tail end that has no guarantee of actually converging.*[2]

Now, in the domain of designing advanced control algorithms for fuel control systems, the

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[1] Typically at the tail end of projects when many problems are detected.

[2] Although in too many instances in practice we somehow manage to get away with it, albeit by incurring heavy costs.

author found by experience that the best weapon was Robust Design. This is simply the disciplined art of asking and answering the following question above all else:

- *What is the sensitivity of this strategy, business plan, customer requirements, system, solution or process etcetera to a normal or exaggerated variation in the relevant factors?*

If for some remote hypothetical reason we had to drastically reduce management training to just one single sentence, the above question would be an excellent candidate. One of the most interesting new management books by Michael Raynor[20] has precisely this theme of designing a Business Strategy that is insensitive to unpredictable variations versus crystal ball strategies that only work by predicting the best possible future outcome. But this is just an opinion. There are others with a similar opinion on Robust Design. This is comforting but Robust Design has only penetrated a small percentage of engineering systems activity as confirmed by Singh et. al. [18] who state that ”While recognizing the practical significance of robust design, it should also be acknowledged that it has had limited depth of penetration into core design practices of major industries. We estimate that the number of uses of robust design today does not exceed 5% of the potential uses”.

5% is significant but not a strong enough evidence of the value of Robust Design. So this chapter uses data obtained from a survey of local mature complex engineering system industries in Colorado to find how *Robustness and Reliabnility* correlates with the biggest hurdles that complex engineering system developers face and other systems skills needed to overcome them.

2.1 Robust Design Basics

The author got into the Robust Design frame of mind several years back by exposure to and practicing the Robust Controls Synthesis philosophy that was developed by Doyle [30] and later fully developed and reported in the standard textbook by Zou et. al. [31]. Despite the heavy math, the attraction was clear: here was a proper grounded approach rooted in mathematics with the objective of delivering the required performance for plants (or family of plants) whose behavior is not known exactly but varies, i.e. where there is uncertainty in plant response.

Shahroudi and Young [32] is among the rarely reported applications of this approach in a heavy industrial mature technology commercial product.[3]

In practicing Robust Controls, the author was constantly pleasantly surprised by effects that were not mentioned in the Robust Controls literature. Not only was the robustness of the product much better, but the level of performance was also much better. This surpassed the original expectation that the performance would be reduced to the basic "good enough" level since the difference would be traded with a gain in robustness. Other side benefits were that the collaboration among the team members was much better and so was the number of gain iterations and overall time and cost of arriving at the final validated product. The next experience was even more surprising when we applied the same exact controller with the same exact gains developed for the GS16 Turbine valve to the smaller GS6 valve[4]. It worked great!. The ability to have a new controller for a device with excellent robust performance with practically no extra development related to algorithm development was a new experience. Even John Doyle [30], regarded as a father of Robust Controls theory does not talk about these side benefits.

So where is the catch? What did we give up in practice to gain the above robustness. This is the answer that one either hears directly from or can deduce indirectly from Robust Design colleagues and literature:

- *For sufficiently complex systems, "Optimal Design" is imaginary.*

Now when is complexity sufficient for the above to hold in practice?

- *Almost any "mature" complex system that is not considered a stand alone component.*

The more complex the system, the more true the above statements. We can intuitively see why the above statements may be true in the context of "Mature and Complex Systems" (e.g. Automobiles, Aircraft, Turbine Fuel Metering Systems etc.). These systems typically evolve in

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[3] As opposed to a prototype or a lab setup. In mature industry, the dominant application of controls algorithm technology typically lags the available theory by about 30 years.

[4] The GS6 valve has a different but similar style motor (i.e. different inertia, resistance, inductance) and different metering section (different friction levels flow forces etc.)

a slow to medium paced technology and market environment. ”Complexity” makes it almost impossible to align the sweet spots of individual subsystems. ”Maturity” makes it difficult to redesign and shift the sweet spot of every other component so that they are perfectly aligned. Even if this improbable alignment was possible under one condition, then it will shift again with aging, operational, usage or manufacturing variations etc. The shift can also be due to incremental innovation or local optimization of a subsystem. The point is that in complex and mature systems, (over)optimization make systems very sensitive.

This may appear to be counter intuitive. As technology evolves, we continue to gain better physical and analytical understanding of physics and can measure significant performance improvements when we optimize the design of individual components (e.g. software, controls, electronics and mechanical subsystems). Yet, the overall systems appear to become extremely sensitive to risks that are tough to predict in advance or handle when they emerge.

So in practice, for complex and mature engineering systems, one is giving up only a mental state by settling for a ”good enough” or ”acceptable”performance level that holds for a very wide range of conditions.

The converse is also true:

- *By striving for optimal performance, one gains a mental state plus a brittle design and looses actual performance that holds for an acceptably wide enough range of conditions.*

The above observations have their roots in engineering. However, Carlson and Doyle [33] give scientific backbone to the observations above. They use the term ”Highly Optimized Tolerance (HOT) is a mechanism that relates evolving structure to power laws in interconnected systems. HOT systems arise where design and evolution create complex systems sharing common features, including (1) high efficiency, performance, and robustness to designed-for uncertainties, (2) hypersensitivity to design flaws and unanticipated perturbations”. They do not quite present an absolute scientific proof for their findings but use a simple example mathematical model of ”forest fire” to illustrate the very similar conclusion:

”Through design and evolution, HOT systems achieve rare structured states which

> are robust to perturbations they were designed to handle, yet fragile to unexpected perturbations and design flaws. As the sophistication of these systems is increased, engineers encounter a series of trade offs between greater productivity or throughput and the possibility of catastrophic failure. Such robustness trade offs are central properties of the complex systems which arise in biology and engineering."

Note that Carlson and Doyle's point is more subtle that the author's point preceding it because they are referring to "Robust yet Fragile" so that even when we include Robustness to known factors in Trade-off to improve output, we may still inadvertently drive toward a catastrophic failure.

A final necessary basic knowledge on robustness is that it is first and foremost determined by the System Architecture. With proper tweaking and tuning of parameters of a given architecture, we can quickly reach the robustness limit set by the architecture. This is a hard limit like a brick wall. You can spend all your company's resources on testing and tweaking the design parameters, but the robustness will not move an iota beyond this inherent limit. Obviously the way out is to change the architecture to one that has a higher inherent limit.

- *Robustness is an Inherent property of the System Architecture. Major improvements are only possible by architectural change and not tweaking the parameters.*

2.1.1 Robust Design Terminology

Here is an example of a robust starting performance of a car: An automobile that starts properly every single time without failure regardless of ambient conditions(pressure, temperature), engine temperature (hot or cold), fuel octane(85, 89, 93) or operator characteristics (patient, impatient, lead foot etc) has a very robust starting function. Using this definition, the majority of new cars today fitted with electronic fuel injection are very robust compared to 20 years ago.

Clausing [17] states that Robustness and Reliability are not the same thing. *Robustness* is a subset of *Reliability* that includes issues like manufacturing or design mistakes. For example, if Honda mistakenly delivers a Civic with a malfunctioning near dead battery, due to a manufacturing mistake, then we can still call the Civic design robust design despite the obvious reliability problem.

A crisper definition of robustness[5]:

- *Robustness is a measure of the insensitivity of a system's response to reasonably common variations in conditions that influence it*

Clausing [16] and [17] calls these conditions noise and gives detailed examples and subdivisions of the following categories:

- Environmental Variations
- Variations in Production
- Variations as the Result of Time and Use

2.1.2 Symptoms of Complex Engineering Systems that are Sensitive

This section is based on personal experience of the author. A comprehensive list of symptoms based on inputs from 690 professionals are identified and grouped together into clusters in section 2.2.

Robustness problems can be hard to diagnose properly because they do not necessarily show up during component tests or under controlled "narrow" conditions. The change in mechanical properties of the space shuttle "O"-Rings with temperature were most likely within spec and never disputed at the the component level. Yet they were a real critical risk that was always lurking in the system for almost 100 successful flights. Mature safety critical reliable systems are required to have extremely low failure rates. But what if the failure rate is reduced from 1 in a million flights to 1 in a 10000 due to a robustness problem? The classical engineering approach to solving this problem is very expensive. I.e. one needs a hugely expensive number of tests to verify the reliability. Clausing [16] gives an excellent solution to this problem discussed in the next section.

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[5] Dan Frey, Professor of Mechanical and Engineering Systems at MIT used a definition very close to this in an email to the author.

So in the domain of complex and mature safety critical systems, Robustness problems are hard to detect and emphasis is obviously on preventing them. But as mentioned earlier only 5% of applications benefit from the Robust Design approach. So how do you know you have robustness problems if your application is in the 95% group? This section gives typical symptoms that highly correlate with robustness problems.

The CSU survey of section 2.2 showed that the biggest complex and dynamic engineering system hurdle faced by 450 mature system engineers[6] in Colorado was *System Requirements Ambiguity and Instability.* System providers obviously prefer a perfect spec because that shifts the majority of the risk to the customer. Requirements are also a matter of legal necessity to allocate scope to suppliers of different subsystems and to hold them accountable. In this sense, the perfect spec should be static, with a fixed scope with perfectly detailed exact description on how compliance is to be validated. Perfect specs translate to perfect ”checklist engineering”. In practice, there is no such thing as perfect specs or check lists. For one thing, check lists alone are not rich enough to capture system interactions or dynamic information or flows or processes. Most complex systems of interest have a very significant dynamic content. For example, a plane has to move to deliver value that is heavily influenced by the price of fuel that most people realize is dynamic and typically goes the wrong direction.

Another practical problem is that perfect specs require a huge amount of work to generate huge amounts of documentation that no one really has time to read or uses fully. If a system has a million parts, and each part is so simple whose requirements can be captured in just one page, we have a million pages of text and check lists. So the tendency would be to read and understand some of the key parts of the requirement and disregard the rest. At an INCOSE presentation on SE tools [34], the presenter claimed that on very complex systems only 40% of requirments are actually read by another person.

Yet the biggest problem with perfect requirements is that it assumes zero uncertainty and shifts all the risk to the customer or toward the commercial end of the business. This side is typically not as knowledgeable about the system details or the best ways to validate nor do

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[6] in the sense of mature complex systems not age.

they typically know exactly what they need before the project kick-off leading to a possible expensive scope change. Even if all these perfect preconditions were satisfied, what do we do when we develop the same product to sell to multiple customers? This gives us our first major symptom of a robustness problem with the final System or the development process:

- *Symptom: Extreme Sensitivity to and inability to cope with Ambiguity and Instability in requirements. Or alternatively, extreme emphasis on deriving perfect specs or intensively engaging the customer to review each item on a huge detailed list of specs*

Other important symptoms that in the author's experience appear to be highly correlated with sensitivity or lack of robustness are listed below:

- *Symptom: Ineffective Risk Management and the Inability to Identify and Bound Uncertainties.*
- *Symptom: (Semi)Infinite Defect loop or projects that remain 99 % complete despite a significant ongoing expenditure of resources.*
- *Symptom: Exponential growth in the amounts of Test Data or Verification and Validation Expense despite a linear growth in the number of new products.*
- *Symptom: Ripple Effects: Seemingly small local incremental changes that cause a large number of changes in other parts of the system.*

Note that the above list of symptoms are very easy to measure. For example, by just trending the data storage capacity allocated to engineering versus the number of new products with time, one can quickly get an indication of whether there is an abnormal growth of data with time. So the problem is not so much with the difficulty of measurement. The problem is in recognizing multiple symptoms of a structural problem such as *Lack of Robustness.*

2.1.3 Why boil the ocean when we have Robust Design?

The "why boil the ocean?" argument was part of a presentation given by Prof. Dan Frey at the Systems Design and Management Conference at MIT in 2007. The holistic vision of

Systems Engineering as given in version 3 of the INCOSE System Engineering Handbook[29] covers every possible aspect of customer value streams, developing, maintaining, operating and decommissioning the system within the full spectrum of Socio-Technical contexts by looking at all the ”-ilities” upfront in the design process. This is obviously a huge task that can grow exponentially with system complexity as the number of possible interactions between the components (in the above multiple dimensions) grows exponentially. It is clear why this vision has emerged. No doubt, by leaving out one of the ’ilities’ or not considering some essential aspect or dimension of the life cycle of the system upfront, very large and expensive mistakes were made that lead to the cumulative check list of issues to grow.

Unfortunately, this ”exhaustive check list engineering” approach is not only very boring, it is also inefficient like ”boiling the ocean” or counterproductive like CAT scanning all parts of all patients that walk into a hospital to make sure most angles are covered. Columbus did not discover America by navigating every inch of space between Europe and America. He used reliable navigation tools like a compass or star charts, a good team and available information from others to accomplish the task. By analogy, we need tools like the ”compass” to rely on so that we can find the desired system design without having to analyze all that is analyzable. In addition, not all the areas of the INCOSE Vision are analyzable with enough certainty because the problems typically fall into a wide range of Socio-Technical or Dynamic spectrum.

At the moment, in the domain of Mature Complex Engineering Systems that covers most complex safety critical systems today (e.g. the Electrical Distribution Grid, Power Generation or Prime Mover Systems, Aircraft, Automobiles etc.) where Robust Systems have the best odds of survival, the *Robust Design Philosophy* appears to be the only well developed compass at this time.

2.2 Strong Correlations with Robust Design

Woodward recently sponsored a System Engineering Chair with the aim of designing a new Systems Engineering program that would serve the needs of the local industry in Colorado. To understand the needs, the author designed an Internet-based survey[7] that was sent to technical and commercial professionals who were asked a very detailed set of questions to identify their type of organization, systems, biggest hurdles or issues and the skills that they believe are the most important to their success. The survey benefited from a number of engineering directors from members of the Industry Advisory Board of the Colorado State University who pushed the survey to the relevant people inside their organizations. We received an excellent response from 690 very experienced professionals (20 years of experience on average) spread among aeronautical, power generation, disc drive, space and other industries with 75% that fully completed the survey.

Other than the typical questions on educational background, experience, market and organizational details, the survey included 29 questions on the *biggest system engineering hurdles* that the respondents faced. In addition, the respondents rated 30 *critical systems engineering skills and competencies* that could be employed to overcome the above hurdles. A very large number of respondents also added, in their own words, what hurdles and competencies they thought were the most important. Their comments ranged from general remarks like:

> ”thank god someone is looking into this...”

to very specific opinions such as:

> ”too many managers are simply unqualified and immature technically and administrative wise. We have so many best practices for each organization that there are a myriad of organizational requirements conflicts in best practices.”

or:

> ”Workforce is not trained to think in as a system, they think and act at too low a level. The organization has not hired and promoted those with the right mindset”.

As the data poured in, a few key points emerged:

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[7] The survey was reviewed by affiliated faculty and industry members who made excellent suggestions for improvement. See the acknowledgment section for details.

- The Database was very rich but the big variation in respondent backgrounds and industries made it difficult to extract useful information by directly looking at summary raw data.
- System Engineering Hurdles appeared to form distinct clusters, analogous to medical conditions that exhibit a number of symptoms, sometimes overlapping.
- Among other items, many respondents rated *Lack of Robust Architectures* as a very significant hurdle and *Robustness and Reliability* as an essential System Engineering Competency.
- The realization that the CSU Survey data was rich enough that one could objectively test the quality of the Robust Design compass. For example, how does robustness problems group into major hurdle (or symptom) clusters and how do *Robustness and Reliability* competencies rank versus other competencies to cure these clustered symptoms.

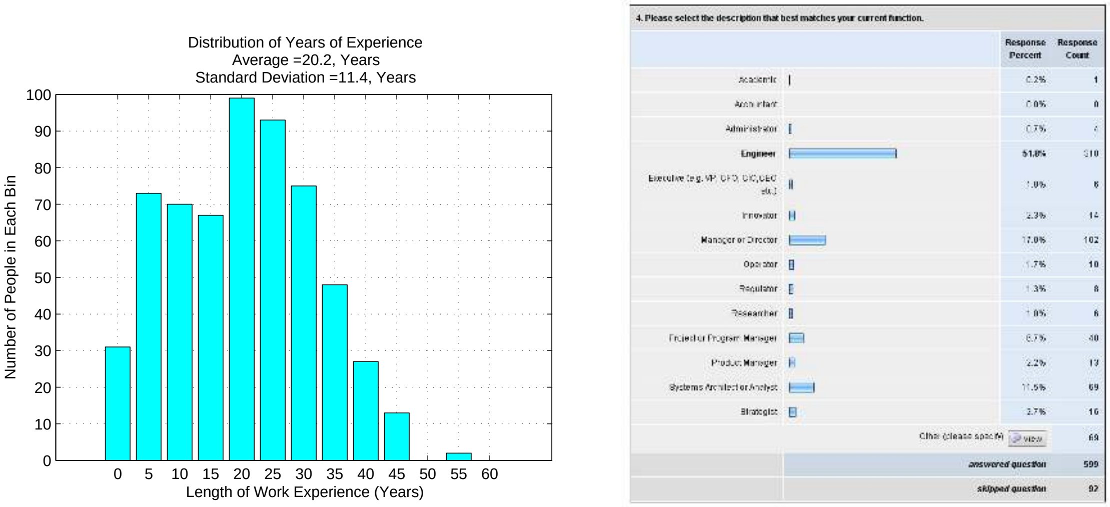
The focus of this section is to find objective answers from the CSU Survey data on how the hurdles (or symptoms) cluster together and which competencies (or cures) are essential in treating them. This is uniques in the sense that most objective references on Robust Design either speak from very personal or isolated experience, or they tend to mainly focus on technical aspects rather than socio-technical issues where human, organizational and business factors are also included. Furthermore, we know that *Robustness and Reliability* is not the only useful skill for treating System issues and we would normally employ a battery of skills. Yet the author is not aware of any references where *Robustness and Reliability* was compared versus other approaches for treating different types of system issues.

2.2.1 Raw Data from Survey

Only the quantitative pieces of information of relevance to the question of Robust Design are included in this section. The actual database also included a large number of personal responses where the respondents input answers in their own words. For example 99 respondents described in their own words, what the biggest Systems Engineering hurdles faced by their organizations were.

Summary Profile of Respondents

Figure 2-1 shows a very experienced population with an average of 20.2 years experience. It also shows that Engineers, Managers (or Director), Systems Architects (or Analysts), and Project (or Program) Managers were the largest functional categories.

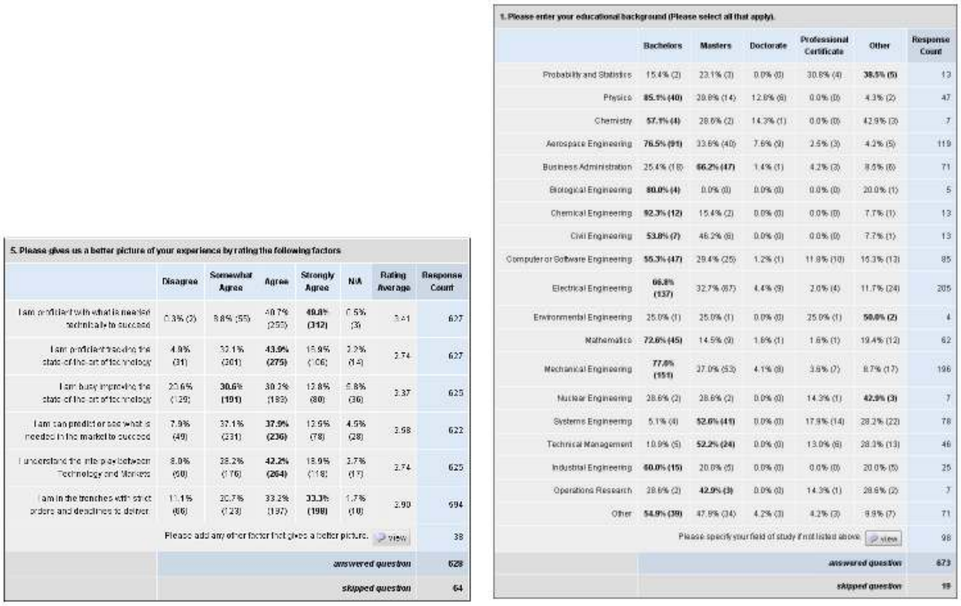


4. Please select the description that best matches your current function.

	Response Percent	Response Count
Academic	0.2%	1
Architect	0.0%	0
Administrator	0.7%	4
Engineer	51.8%	310
Executive (e.g. VP, CFO, CIO, CEO etc.)	1.0%	6
Innovator	2.3%	14
Manager or Director	17.0%	102
Operator	1.7%	10
Regulator	1.3%	8
Researcher	1.0%	6
Project or Program Manager	6.7%	40
Product Manager	2.2%	13
Systems Architect or Analyst	11.5%	69
Strategist	2.7%	16
Other (please specify) view		69
	answered question	599
	skipped question	92

Figure 2-1: Distribution of Survey Respondents by Length of work experience and Function.

Figure 2-2 shows that the proficiency of the population is technical with moderate business and market orientation. It also shows that the majority are in the trenches with strict deadlines to deliver, or alternatively, this population appears to be highly loaded. The figure also gives the educational background. The table in the figure shows the largest groups were Electrical(205), Mechanical(196), Aerospace(119), Computer (or Software 85) and Systems Engineers (79). There was also a significant number Business Administration (79) and Technical Management (46).



5. Please gives us a better picture of your experience by rating the following factors

	Disagree	Somewhat Agree	Agree	Strongly Agree	N/A	Rating Average	Response Count
I am proficient with what is needed technically to succeed	0.3% (2)	8.8% (55)	40.7% (255)	**49.8% (312)**	0.5% (3)	3.41	627
I am proficient tracking the state-of-the-art of technology	4.9% (31)	32.1% (201)	**43.9% (275)**	16.9% (106)	2.2% (14)	2.74	627
I am busy improving the state-of-the-art of technology	20.6% (129)	**30.6% (191)**	30.2% (189)	12.8% (80)	5.8% (36)	2.37	625
I am can predict or see what is needed in the market to succeed	7.9% (49)	37.1% (231)	**37.9% (236)**	12.5% (78)	4.5% (28)	2.58	622
I understand the inter-play between Technology and Markets	8.0% (50)	28.2% (176)	**42.2% (264)**	18.9% (118)	2.7% (17)	2.74	625
I am in the trenches with strict orders and deadlines to deliver	11.1% (66)	20.7% (123)	33.2% (197)	**33.3% (198)**	1.7% (10)	2.90	594
	Please add any other factor that gives a better picture.					view	38
						answered question	**628**
						skipped question	**64**

1. Please enter your educational background (Please select all that apply).

	Bachelors	Masters	Doctorate	Professional Certificate	Other	Response Count
Probability and Statistics	15.4% (2)	23.1% (3)	0.0% (0)	30.8% (4)	**38.5% (5)**	13
Physics	**85.1% (40)**	29.8% (14)	12.8% (6)	0.0% (0)	4.3% (2)	47
Chemistry	**57.1% (4)**	28.6% (2)	14.3% (1)	0.0% (0)	42.9% (3)	7
Aerospace Engineering	**76.5% (91)**	33.6% (40)	7.6% (9)	2.5% (3)	4.2% (5)	119
Business Administration	25.4% (18)	**66.2% (47)**	1.4% (1)	4.2% (3)	8.5% (6)	71
Biological Engineering	**80.0% (4)**	0.0% (0)	0.0% (0)	0.0% (0)	20.0% (1)	5
Chemical Engineering	**92.3% (12)**	15.4% (2)	0.0% (0)	0.0% (0)	7.7% (1)	13
Civil Engineering	**53.8% (7)**	46.2% (6)	0.0% (0)	0.0% (0)	7.7% (1)	13
Computer or Software Engineering	**55.3% (47)**	29.4% (25)	1.2% (1)	11.8% (10)	15.3% (13)	85
Electrical Engineering	**66.8% (137)**	32.7% (67)	4.4% (9)	2.0% (4)	11.7% (24)	205
Environmental Engineering	25.0% (1)	25.0% (1)	0.0% (0)	25.0% (1)	**50.0% (2)**	4
Mathematics	**72.6% (45)**	14.5% (9)	1.6% (1)	1.6% (1)	19.4% (12)	62
Mechanical Engineering	**77.0% (151)**	27.0% (53)	4.1% (8)	3.6% (7)	8.7% (17)	196
Nuclear Engineering	28.6% (2)	28.6% (2)	0.0% (0)	14.3% (1)	**42.9% (3)**	7
Systems Engineering	5.1% (4)	**52.6% (41)**	0.0% (0)	17.9% (14)	28.2% (22)	78
Technical Management	10.9% (5)	**52.2% (24)**	0.0% (0)	13.0% (6)	28.3% (13)	46
Industrial Engineering	**60.0% (15)**	20.0% (5)	0.0% (0)	0.0% (0)	20.0% (5)	25
Operations Research	28.6% (2)	**42.9% (3)**	0.0% (0)	14.3% (1)	28.6% (2)	7
Other	**54.9% (39)**	47.9% (34)	4.2% (3)	4.2% (3)	9.9% (7)	71
	Please specify your field of study if not listed above.				view	98
					answered question	**673**
					skipped question	**19**

Figure 2-2: Breakdown of respondents by Proficiency and Education.

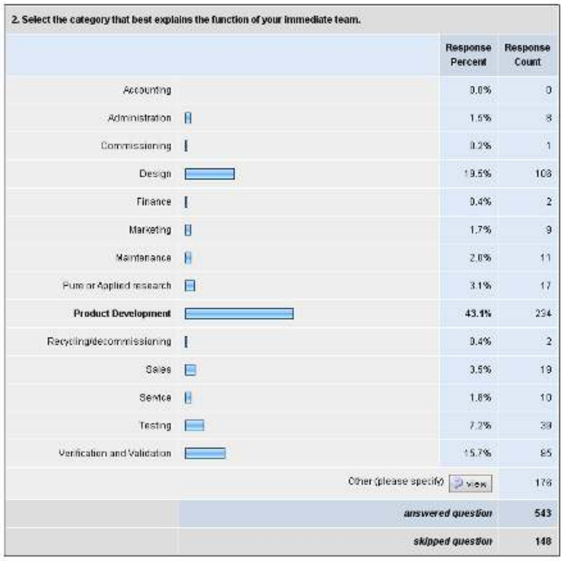
Profile of Organization

Figure 2-3 shows the distribution of the function of the team or unit where the respondents work. Product Development(234), Design(106), Verification and Validation (85) and Testing (39) were the largest groups.

Figure 2-4 shows that the data covers a full range of spectrum with regards to Pace of Technology and Markets. The key mode of innovation is incremental(60.3 %) or Incremental plus Radical (34.8 %). This is typical for slow to medium paced mature industries with complex engineering system products that require a high levels of robustness and reliability that is the main focus of this chapter.

Hurdles and Competency Data

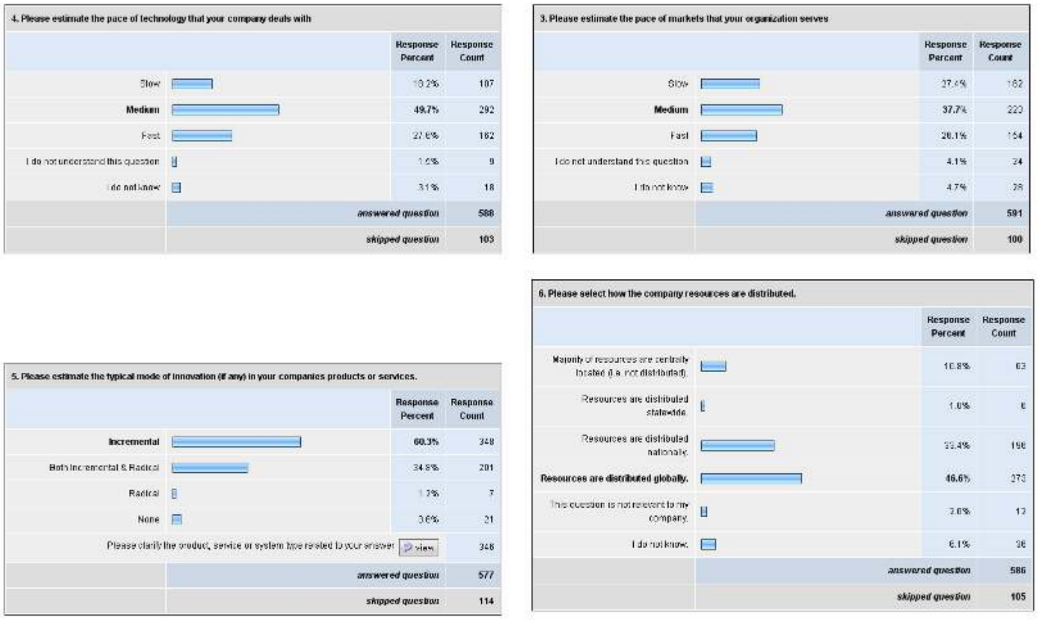
The survey asked 29 questions on the biggest systems engineering ”hurdles” that the respondents faced in their organizations, grouped into Human Factor Hurdle (HFH), Project (or Program) Management Hurdle (PMH), Business Factor Hurdles (BFH) and System Factor Hurdles (SFH). The tables in figures 2-5 summarizes the data collected on hurdles.



2. Select the category that best explains the function of your immediate team.

	Response Percent	Response Count
Accounting	0.0%	0
Administration	1.5%	8
Commissioning	0.2%	1
Design	19.5%	106
Finance	0.4%	2
Marketing	1.7%	9
Maintenance	2.0%	11
Pure or Applied research	3.1%	17
Product Development	**43.1%**	234
Recycling/decommissioning	0.4%	2
Sales	3.5%	19
Service	1.8%	10
Testing	7.2%	39
Verification and Validation	15.7%	85
Other (please specify)	view	176
	answered question	**543**
	skipped question	**148**

Figure 2-3: Distribution of Survey Respondents by Function of Team or Unit.



4. Please estimate the pace of technology that your company deals with

	Response Percent	Response Count
Slow	18.2%	107
Medium	**49.7%**	292
Fast	27.6%	162
I do not understand this question	1.5%	9
I do not know	3.1%	18
	answered question	**588**
	skipped question	**103**

3. Please estimate the pace of markets that your organization serves

	Response Percent	Response Count
Slow	27.4%	162
Medium	**37.7%**	223
Fast	26.1%	154
I do not understand this question	4.1%	24
I do not know	4.7%	28
	answered question	**591**
	skipped question	**100**

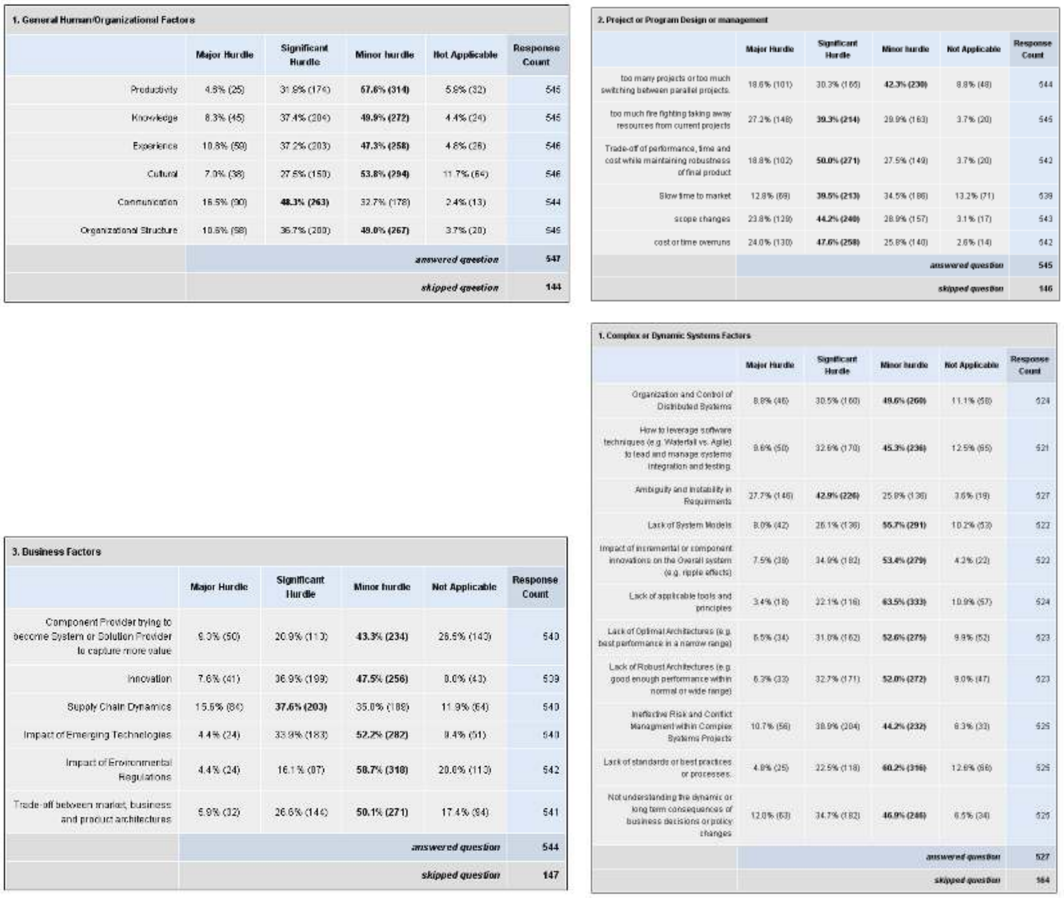
5. Please estimate the typical mode of innovation (if any) in your companies products or services.

	Response Percent	Response Count
Incremental	**60.3%**	348
Both Incremental & Radical	34.8%	201
Radical	1.2%	7
None	3.6%	21
Please clarify the product, service or system type related to your answer	view	348
	answered question	**577**
	skipped question	**114**

6. Please select how the company resources are distributed.

	Response Percent	Response Count
Majority of resources are centrally located (i.e. not distributed).	10.8%	63
Resources are distributed statewide.	1.0%	6
Resources are distributed nationally.	33.4%	196
Resources are distributed globally.	**46.6%**	273
This question is not relevant to my company.	2.0%	12
I do not know.	6.1%	36
	answered question	**586**
	skipped question	**105**

Figure 2-4: Pace of Technology, Pace of Market, Innovation Mode and Resource Distribution of organizations that contributed data.



1. General Human/Organizational Factors

	Major Hurdle	Significant Hurdle	Minor hurdle	Not Applicable	Response Count
Productivity	4.6% (25)	31.9% (174)	**57.6% (314)**	5.9% (32)	545
Knowledge	8.3% (45)	37.4% (204)	**49.9% (272)**	4.4% (24)	545
Experience	10.8% (59)	37.2% (203)	**47.3% (258)**	4.8% (26)	546
Cultural	7.0% (38)	27.5% (150)	**53.8% (294)**	11.7% (64)	546
Communication	16.5% (90)	**48.3% (263)**	32.7% (178)	2.4% (13)	544
Organizational Structure	10.6% (58)	36.7% (200)	**49.0% (267)**	3.7% (20)	545
				answered question	**547**
				skipped question	**144**

2. Project or Program Design or management

	Major Hurdle	Significant Hurdle	Minor hurdle	Not Applicable	Response Count
too many projects or too much switching between parallel projects.	18.6% (101)	30.3% (165)	**42.3% (230)**	8.8% (48)	544
too much fire fighting taking away resources from current projects	27.2% (148)	**39.3% (214)**	29.9% (163)	3.7% (20)	545
Trade-off of performance, time and cost while maintaining robustness of final product	18.8% (102)	**50.0% (271)**	27.5% (149)	3.7% (20)	542
Slow time to market	12.8% (69)	**39.5% (213)**	34.5% (186)	13.2% (71)	539
scope changes	23.8% (129)	**44.2% (240)**	28.9% (157)	3.1% (17)	543
cost or time overruns	24.0% (130)	**47.6% (258)**	25.8% (140)	2.6% (14)	542
				answered question	**545**
				skipped question	**146**

3. Business Factors

	Major Hurdle	Significant Hurdle	Minor hurdle	Not Applicable	Response Count
Component Provider trying to become System or Solution Provider to capture more value	9.3% (50)	20.9% (113)	**43.3% (234)**	26.5% (143)	540
Innovation	7.6% (41)	36.9% (199)	**47.5% (256)**	8.0% (43)	539
Supply Chain Dynamics	15.6% (84)	**37.6% (203)**	35.0% (189)	11.9% (64)	540
Impact of Emerging Technologies	4.4% (24)	33.9% (183)	**52.2% (282)**	9.4% (51)	540
Impact of Environmental Regulations	4.4% (24)	16.1% (87)	**58.7% (318)**	20.8% (113)	542
Trade-off between market, business and product architectures	5.9% (32)	26.6% (144)	**50.1% (271)**	17.4% (94)	541
				answered question	**544**
				skipped question	**147**

1. Complex or Dynamic Systems Factors

	Major Hurdle	Significant Hurdle	Minor hurdle	Not Applicable	Response Count
Organization and Control of Distributed Systems	8.8% (46)	30.5% (160)	**49.6% (260)**	11.1% (58)	524
How to leverage software techniques (e.g. Waterfall vs. Agile) to lead and manage systems integration and testing.	9.6% (50)	32.6% (170)	**45.3% (236)**	12.5% (65)	521
Ambiguity and instability in Requirements	27.7% (146)	**42.9% (226)**	25.8% (136)	3.6% (19)	527
Lack of System Models	8.0% (42)	26.1% (136)	**55.7% (291)**	10.2% (53)	522
Impact of incremental or component innovations on the Overall system (e.g. ripple effects)	7.3% (38)	34.9% (182)	**53.4% (279)**	4.2% (22)	522
Lack of applicable tools and principles	3.4% (18)	22.1% (116)	**63.5% (333)**	10.9% (57)	524
Lack of Optimal Architectures (e.g. best performance in a narrow range)	6.5% (34)	31.0% (162)	**52.6% (275)**	9.9% (52)	523
Lack of Robust Architectures (e.g. good enough performance within normal or wide range)	6.3% (33)	32.7% (171)	**52.0% (272)**	9.0% (47)	523
Ineffective Risk and Conflict Managment within Complex Systems Projects	10.7% (56)	38.9% (204)	**44.2% (232)**	6.3% (33)	525
Lack of standards or best practices or processes.	4.8% (25)	22.5% (118)	**60.2% (316)**	12.6% (66)	525
Not understanding the dynamic or long term consequences of business decisions or policy changes	12.0% (63)	34.7% (182)	**46.9% (246)**	6.5% (34)	525
				answered question	**527**
				skipped question	**164**

Figure 2-5: Rated Human, Business, Project Management and Complex System Factors that form the biggest Systems Engineering Hurdles (or symptoms) faced by survey respondents.

The Survey also asked 30 questions on the importance of General and Specialized Systems Engineering Skills (or cures), to over come the above hurdles. Figure 2-6 shows the summary of the ratings.

Several skills directly jump out from the figure 2-6 as essential. For example, System Requirements and its close cousin, Integration, Verification and Validation were the highest ranked general skills. Another example, it is very interesting and that Leadership that is not a classical technical field, was one of the highest ranked Specialized Skill in Systems Engineering. However, since several types of organizations and people are responding, one must be careful about drawing direct conclusions from summary data because, for example the pool of people who rated Leadership essential may not be the same people that rated System Requirements as essential. Moreover, the two groups may disagree on what symptoms these skills cure.

Please note that the majority of question fields in the survey data within each main question category were randomized in order to remove biases and reflection of the design of survey in the responses. For example, when rating Business factors, the first question that two respondents in sequence saw was Innovation versus Supply Chain Dynamics. Some questions did not need randomization, however. For example, the education fields in figure 2-2 were seen by the respondents in alphabetical order to make it quick and convenient to find their selection.

The summary data of this section is interesting and included for documentation of the data and the survey questions. But the main question still remains: How do *Systems Engineering Hurdles* (or symptoms) cluster together and how do *Systems Engineering Skills* rank in overcoming (or curing) these hurdles?

2.2.2 Statistical Cluster Analysis

This section first extracts clusters in the hurdles data using Principal Component Analysis. Each cluster then serves as a correlated group of symptoms similar to a medical condition that exhibits a number of symptoms by analogy. Cross correlation and Coherence techniques then enable the ranking of cause and effect relationship between Systems Engineering Skills and the clusters in System Engineering Hurdles.

1. Please rate the importance of the following general systems engineering competencies:

	Not Important	Important	Essential	Rating Average	Response Count
Concept or Solution Generation and Selection	2.9% (15)	**51.9% (269)**	45.2% (234)	2.42	518
Super system or System of Systems Issues	13.5% (70)	**56.7% (295)**	29.8% (155)	2.16	520
Business and Technology	9.9% (52)	**66.9% (350)**	23.1% (121)	2.13	523
Systems Requirements	0.8% (4)	18.7% (98)	**80.5% (421)**	2.80	523
Functional Design and Analysis	0.8% (4)	37.1% (195)	**62.1% (326)**	2.61	525
Systems Architecture: Function, Form, Process etc.	1.3% (7)	39.8% (208)	**58.9% (308)**	2.58	523
Robustness and Reliability	1.3% (7)	36.3% (189)	**62.4% (325)**	2.61	521
Systems Integration, Verification and Validation	0.6% (3)	21.2% (111)	**78.2% (410)**	2.78	524
Probability and Statistics	13.2% (69)	**67.6% (353)**	19.2% (100)	2.06	522
(Large Scale) System Modeling and Simulation	6.1% (32)	**52.2% (273)**	41.7% (218)	2.36	523
				answered question	525
				skipped question	166

1. Please rate the importance of the following specialized skills in systems engineering:

	Not Important	Important	Essential	I don't Know	Rating Average	Response Count
Multidisciplinary Systems Design	2.9% (15)	39.1% (202)	**54.5% (281)**	3.5% (18)	2.53	518
Optimization Methods	6.0% (31)	**63.1% (326)**	24.8% (128)	6.2% (32)	2.20	517
Operations Research	16.8% (87)	**55.9% (289)**	16.1% (83)	10.8% (58)	2.00	517
Systems Project and Risk Management	1.9% (10)	38.1% (197)	**58.4% (302)**	1.5% (8)	2.57	517
Systems Reliability	1.6% (8)	32.8% (168)	**64.5% (330)**	1.2% (6)	2.64	512
Risk and Benefit Analysis	2.1% (11)	**48.4% (250)**	48.0% (248)	1.5% (8)	2.47	517
Complex System Technical and Business Dynamics	6.6% (34)	**55.8% (289)**	26.8% (139)	10.7% (55)	2.23	518
Software Systems Engineering	3.5% (18)	34.5% (179)	**58.8% (305)**	3.3% (17)	2.57	519
Finance, Economics and Cost Estimation	6.6% (34)	**61.2% (316)**	27.3% (141)	4.8% (25)	2.22	516
System Test and Evaluation	0.8% (4)	24.7% (127)	**73.2% (376)**	1.4% (7)	2.73	514
Lean Systems (e.g. JIT, TQC, Continuous Improvement, etc.)	14.1% (73)	**55.6% (287)**	21.5% (111)	8.7% (45)	2.08	516
Manufacturing, Production and Operations	6.0% (31)	**49.0% (253)**	41.7% (215)	3.3% (17)	2.37	516
Supply Chain Dynamics	11.7% (60)	**53.8% (277)**	26.8% (138)	7.8% (40)	2.16	515
Optimization	4.6% (24)	**64.9% (336)**	25.9% (134)	4.6% (24)	2.22	518
Leadership	1.9% (10)	31.7% (164)	**64.2% (332)**	2.1% (11)	2.64	517
Organizing for Innovation in the Market	15.6% (81)	**51.0% (264)**	22.0% (114)	11.4% (59)	2.07	518
Business and Technology Strategy	10.4% (54)	**51.2% (265)**	31.9% (165)	6.6% (34)	2.23	518
Engineering Ethics and Legal Considerations	6.4% (33)	**54.6% (283)**	34.9% (181)	4.1% (21)	2.30	518
Negotiation	13.4% (69)	**57.0% (294)**	23.1% (119)	6.6% (34)	2.10	518
Value Mapping from Creation to Capture	11.8% (61)	**56.9% (295)**	18.1% (94)	13.1% (68)	2.07	518
					answered question	519
					skipped question	172

Figure 2-6: Rated General (Left Table) and Specialized (Right Table) System Engineering Competencies (Cures) that are needed to Overcome the Hurdles (or symptoms) shown in figure 2-5.

Principal Component Cluster Analysis of Systems Engineering Hurdles (Symptoms)

Using the SPSS software, Prof. Jim Zumbrunnen at CSU extracted the clusters shown in figure 2-7. The extraction method was Principal Component Analysis for correlation and the rotation method used was Varimax with Kaiser normalization. Component loadings higher than 0.5 were highlighted for each cluster. Clusters 1 to 4 represent 12.2, 10.6, 9.5 and 8.5 percent variation in the data respectively, so that they cumulatively represent 40.8 percent of the variation[8] seen in the data. In principle, we need 29 clusters to fully represent 100 percent of variance for the 29 Hurdles. However, once the significance of these clusters are plotted in an Eigenvalue Scree plot, we see that the last 26 clusters become increasingly less significant.

The plotted numbers in figure 2-7 are the individual component loadings. Higher values than 0.5 are highlighted for a quick visual pick of the most significant members of each cluster. For example, in Culster 1, *Trade-off between market, business and product architectures* , and *Lack of Robust Architectures* are the two most significant members of the biggest Cluster 1.

Please note that figure 2-7 is very useful for interpretation because:

- there is little overlap between the clusters and no overlap among the most significant components that are highlighted.
- members of a cluster are spread across two or more categories of the hurdles. For example Cluster 1 includes members from System Factor Hurdles (SFH), Business Factor Hurdles (BFH) and Program Management Hurdles (PMH). This helps a great deal in finding strong affinities across the categories.

Looking at Cluster 1 components in figure 2-7, we see that *(PMH) Slow time to market*, *(BFH) Trade-off between Market, Business and Product Architectures* and *(BFH) Component Provider trying to become a System Provider to capture more value* are highly correlated symptoms to *(SFH) Lack of Robust Architectures*. Now, executives may talk about the former Project Management and Business Factors as real problems that their organizations are facing but they

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[8] This is the percentage of variance in Rotation Sums of Squared Loadings.

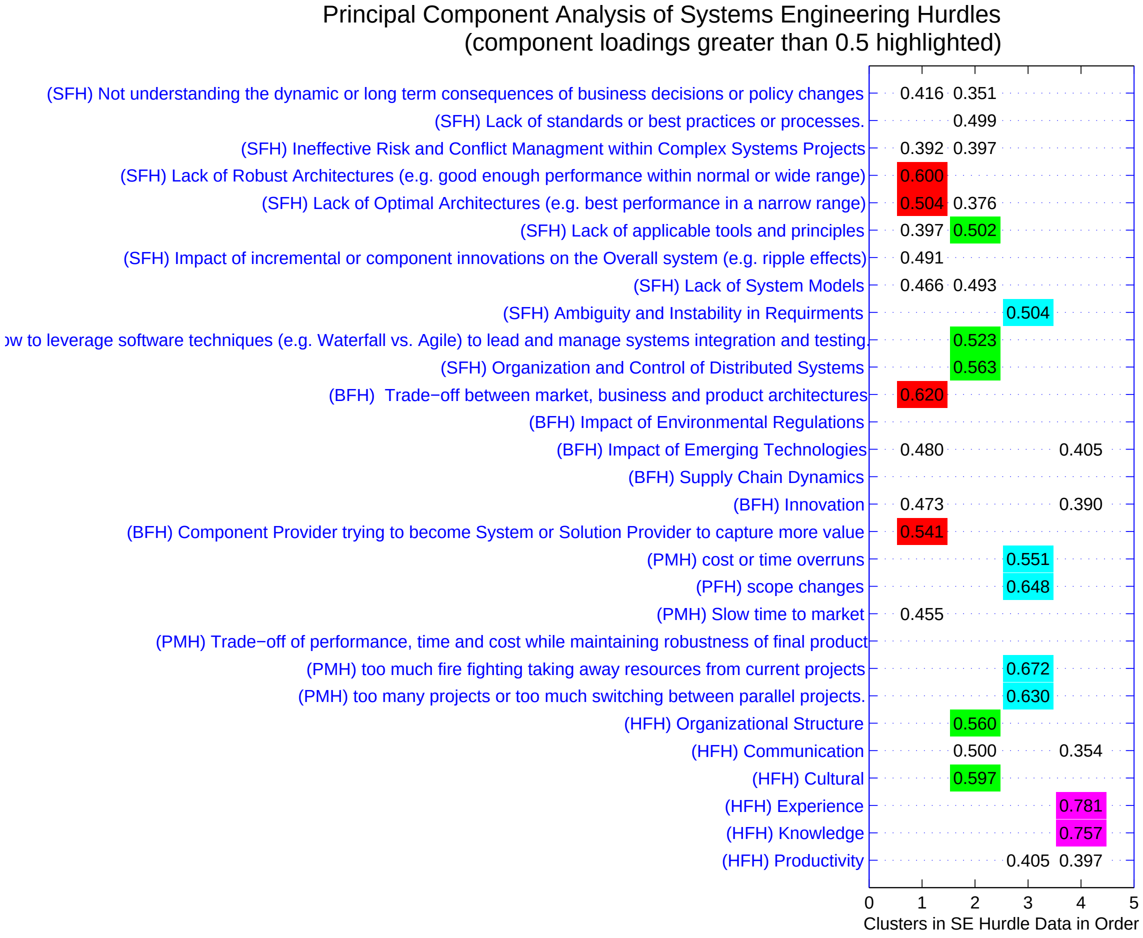


Figure 2-7: Clusters extracted by Principal Component Analysis of System Engineering Hurdles Data.

may not know that these symptoms may be highly correlated with the System Factors such as Lack of Robust Architectures. Based on data from 690 experienced professionals, among which a significant portion have Technical Management or Business Administration backgrounds, we have solid evidence that these symptoms correlate better than others in the data. Furthermore, other Factors such as Experience, Knowledge and Productivity, a very typical focus for organizations, are not related in a significant way to other symptoms in Cluster 1. So we may for example conclude that a component provider who wants to become a system or a solution provider, would typically do better to focus on Lack of Robust Architectures (if there are problems there) than Productivity.

Another interesting find in Cluster 1 is that Lack of Robust Architectures and Lack of Optimal Architectures are in the same cluster. This could mean that there is not much differentiation between the two hurdles in the respondents mind, i.e they may see them as the same issue with different wording. Or it could mean that these symptoms coexists. For example, it was mentioned earlier that when the author improved the robustness of the GS16 application, several team members saw it as an improvement in performance and not robustness, the reason being that the performance optimized predecessor, only delivered the best performance on the bench and lost performance as conditions varied, such that ”good enough” performance over a wide operating region of the Robust design in practice delivered higher performance than the optimal design that in practice rarely ran at its best narrow optimal region.

Now ideally, one would have to go deeper to see if we can detect particular overriding attributes of respondents or organizations. For example, it would be nice to find out the mix of Manager versus Engineers that strongly identify with Cluster 1. However deeper analysis is beyond the scope of this thesis. Only the following major take aways from principal component analysis are required for this thesis:

- Four major clusters were extracted that represent 40.8 percent of variation in the data
- The components of the highest ranked cluster are very closely related to the topics that concern this thesis, in particular, the thesis touches on the following items in this or other chapters:

1. (BFH) Component Provider trying to become System or Solution Provider
2. (BFH) Impact of Emerging Technologies
3. (SFH) Lack of Robust Architectures
4. (PMH) Slow Time to Market
5. (PMH) Trade-off between market, business and product architectures
6. (SFH) Impact of Incremental or Component Innovation on the Overall System
7. (SFH) Not Understanding the dynamic or long term consequences of business decisions or policy changes

Cause and Effect relationship between Systems Engineering Competencies (Cures) and the Four Hurdles (Symptoms) Clusters

This section gives the final piece of the puzzle, that is how do the individual skills rank with respect to overcoming (or curing) each of the 4 clusters extracted by principal component analysis in the previous section.

Figure 2-8 shows the four step process to compute the rankings:

1. In step 1, the data is first normalized by removing the means and dividing by the standard deviation followed by purging NaN (Not a Number) entries that arise when a respondent leaves a question blank.

2. In Step 2, the variance of coherence[9] between each Hurdle/Skill pair is computed. When we measure the coherence for a Hurdle/Skill pair we see that it rises and falls at different frequencies. This means that the quality of the input/output or cause/effect relationship varies according to the size of the groups that we use to sample the data. The variance

---

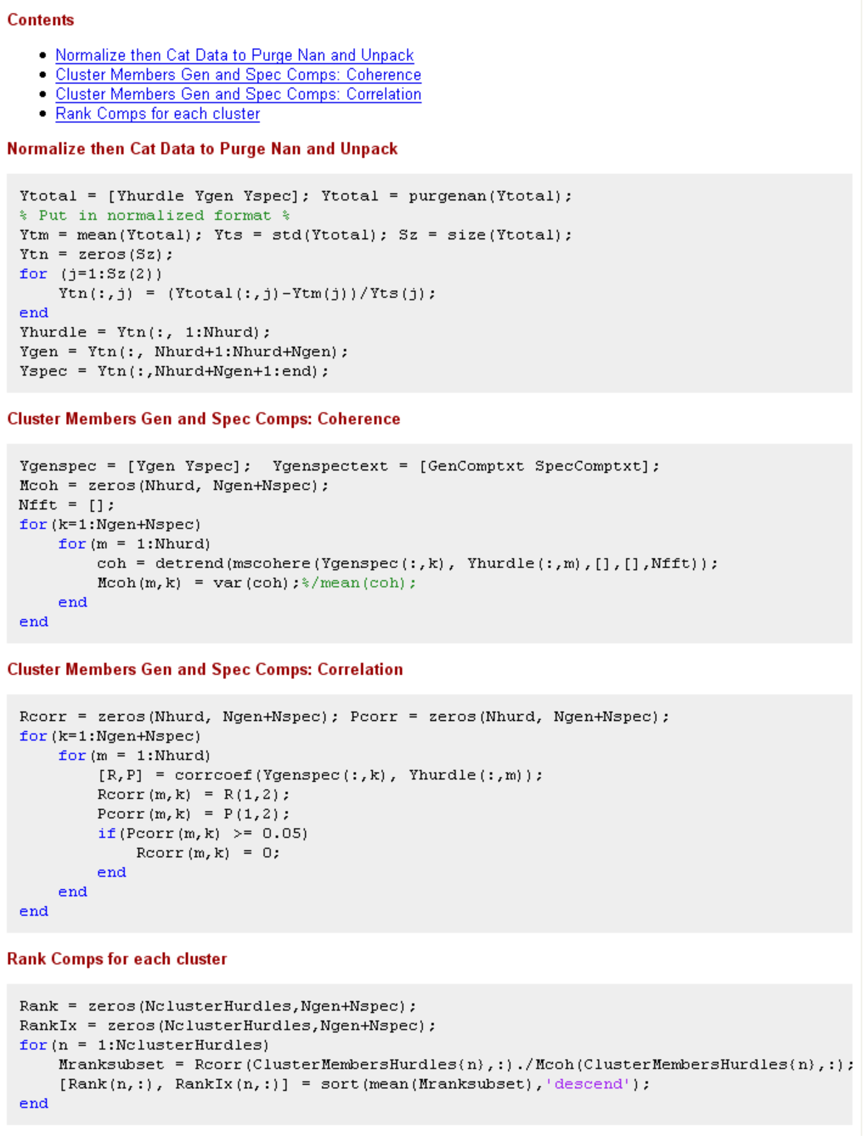
[9] Coherence is a technique used often in Control & Dynamics or Signal Processing. It is an excellent measure of the linear (in the frequency domain sense) cause and effect relationship between input and output signals of a system. For example, if the signal to noise ratio on the input or the output signal is low, or if the output pattern looks too different and cannot be explained by a linear transfer function applied to the input, then the measure of coherence will be low.

of the coherence then measures the instability of the cause/effect relationship of each Hurdle/Skill pair within the total population. Its inverse then measures the insensitivity of the Cause/Effect relationship to how we group people or alternatively our confidence that the cause/effect relationship holds across the total population.

3. In Step 3, we calculate the cross correlation coefficient of each Hurdle/Skill pair. Note that this also gives a null hypothesis probability typically referred to as P-values, so that correlations with P-values great than 0.05 are considered to be unreliable and ignored.

4. In Step 4, a merit value is computed for each Hurdle/Skill pair by weighting the correlation coefficients by the inverse of the variance of the coherence, for correlations with P-values below the threshold value of 0.05. Above this threshold, the merit value is set to zero. In this way, the merit value represents a steady or stable measure of the cause and effect relationship for a Hurdles/Skill pair within the population. An alternative explanation is that this picks out strong correlations that cause the least difference of opinion within the total population. Now since each cluster, contains a number of Hurdles, then the rank is based on the average merit values of the set of [Hurdle1/Skill, Hurdle2/Skill,..., HurdleN/Skill] pairs in a cluster.

The final bottom line results of this analysis is shown in figure 2-9 for Cluster 1. The top part of the figure (the smaller bar plot) shows the Hurdles that belong to Cluster 1, ranked in order of significance by their principal component loading value. So this part of the figure is a different way to visualize the same information as in figure 2-7 for Cluster 1. Note that each item is tagged by its Hurdle category for a quick visual pick of categories included in each cluster. These categories are: *(HFH)* Human Factor Hurdle, *(BFH)* Business Factor Hurdle, *(PMH)* Project Management Hurdle, and *(SFH)* System Factor Hurdle. The lower part of the figure is the new information that ranks the System Engineering Competencies or Skills on how effective they are at overcoming the group of Hurdles in Cluster 1. The System Engineering Competencies are also tagged *(GSC)* General System Competency and *(SSC)* Specialized System Competency for a quick visual pick. The way to read and interpret this plot is:



Contents

- Normalize then Cat Data to Purge Nan and Unpack
- Cluster Members Gen and Spec Comps: Coherence
- Cluster Members Gen and Spec Comps: Correlation
- Rank Comps for each cluster

Normalize then Cat Data to Purge Nan and Unpack

```
Ytotal = [Yhurdle Ygen Yspec]; Ytotal = purgenan(Ytotal);
% Put in normalized format %
Ytm = mean(Ytotal); Yts = std(Ytotal); Sz = size(Ytotal);
Ytn = zeros(Sz);
for (j=1:Sz(2))
    Ytn(:,j) = (Ytotal(:,j)-Ytm(j))/Yts(j);
end
Yhurdle = Ytn(:, 1:Nhurd);
Ygen = Ytn(:, Nhurd+1:Nhurd+Ngen);
Yspec = Ytn(:,Nhurd+Ngen+1:end);
```

Cluster Members Gen and Spec Comps: Coherence

```
Ygenspec = [Ygen Yspec];  Ygenspectext = [GenComptxt SpecComptxt];
Mcoh = zeros(Nhurd, Ngen+Nspec);
Nfft = [];
for(k=1:Ngen+Nspec)
    for(m = 1:Nhurd)
        coh = detrend(mscohere(Ygenspec(:,k), Yhurdle(:,m),[],[],Nfft));
        Mcoh(m,k) = var(coh);%/mean(coh);
    end
end
```

Cluster Members Gen and Spec Comps: Correlation

```
Rcorr = zeros(Nhurd, Ngen+Nspec); Pcorr = zeros(Nhurd, Ngen+Nspec);
for(k=1:Ngen+Nspec)
    for(m = 1:Nhurd)
        [R,P] = corrcoef(Ygenspec(:,k), Yhurdle(:,m));
        Rcorr(m,k) = R(1,2);
        Pcorr(m,k) = P(1,2);
        if(Pcorr(m,k) >= 0.05)
            Rcorr(m,k) = 0;
        end
    end
end
```

Rank Comps for each cluster

```
Rank = zeros(NclusterHurdles,Ngen+Nspec);
RankIx = zeros(NclusterHurdles,Ngen+Nspec);
for(n = 1:NclusterHurdles)
    Mranksubset = Rcorr(ClusterMembersHurdles{n},:)./Mcoh(ClusterMembersHurdles{n},:);
    [Rank(n,:), RankIx(n,:)] = sort(mean(Mranksubset),'descend');
end
```

Figure 2-8: Matlab Script used for ranking individual System Engineering Competencies (Cures) to overcome System Engineering Hurdles (Symptoms) Clusters.

- *The largest group of like minded people agree on 12 out of 29 system hurdles (or symptoms) to be the biggest issues their organizations faced. These 12 hurdles can be considered as multiple symptoms of a single condition (or Cluster) because single individuals within this group tend to rate problems that are causing the most pain at the moment or the ones that have caused huge pain in the past such that they still linger in memory. Now using the expertise of the total population, we can see that the Specialized System Competency called* (SSC) Complex System Technical and Business Dynamics *is the most effective skill (or cure) to overcome the group of Hurdles (or symptoms) in Cluster 1.*

Now the lower bar chart should be viewed as a scree plot. So the top 5 skills together would go a long way (or the biggest bang for the buck) to curing the Cluster 1 group of symptoms, and they would be the best top 5 out of 30 choices. Please note that some bars are zero and some negative. The zero bars are due to forcing the correlation to zero when the P-value is higher than 0.05. The negative correlations in figure 2-9 are interesting in that it is not clear why for

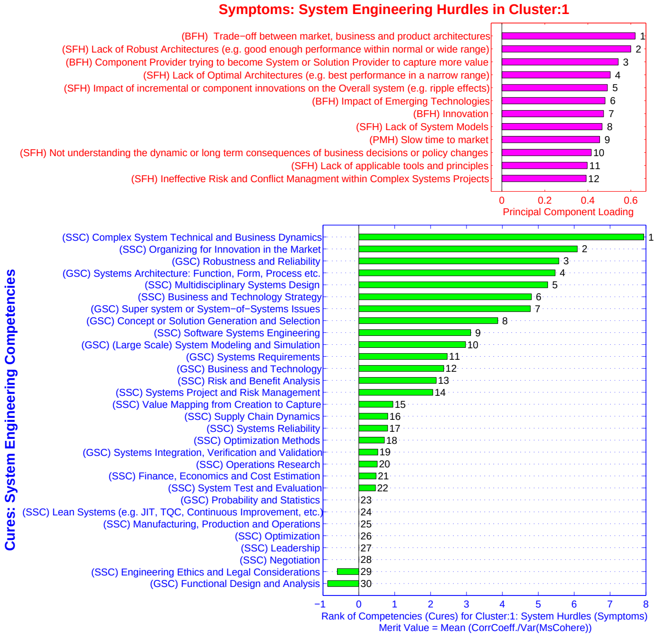


Figure 2-9: Ranking of System Engineering Skills (or Cures) for Cluster 1 Hurdles (or Symptoms).

example *(SSC) Engineering Ethics and Legal Considerations* would adversely affect the group of symptoms in Cluster 1. This is likely to be a reflection of the accumulation of errors and inconsistencies in the data rather than a real effect. However, this is a mute point here since we are trying to extract strong consistent positive correlations and not weak negative ones.

Figure 2-10 to 2-12 show the rest of the rankings for Clusters 2 to 4. An interesting find in Cluster 4 is that *(GSC) Robustness and Reliability* is clearly a huge hitter regarding soft Business or Human type Hurdles included in Cluster 4.

Furthermore, in the most significant Cluster number 1, *(SFH) Lack of Robust Architectures*is a top (Ranked 2nd) Hurdle. But it is not even in the list of Hurdles for like minded people in Clusters 3 and 4. Yet this skill still enjoys a top position in Clusters 3 and 4.

Hence, the major take away of this analysis by looking across the results of the four clusters is:

- *(GSC) Robustness and Reliability is a TOP HITTER on a very wide range of Socio-Technical System Type Hurdles that Organizations Face.*

2.3 Conclusions on Robust Design

Based on personal experience of the author on implementing Robust Controls philosophy in Woodward Turbine Fuel System products [35] [32], very reputable robust design sources [33] [16] [17] [30], [31], [18] and analysis of a detailed survey of 690 experienced professionals with technical and managerial/business backgrounds in organizations that work on complex engineering systems, the major conclusion or take away from this chapter is:

- *(GSC) Robustness and Reliability is a TOP HITTER on a very wide range of Socio-Technical System Type Hurdles that Organizations Face.*

The subsection 2.1.2 described the typical symptoms of engineering systems that are sensitive based on the personal experience of the author, such as:

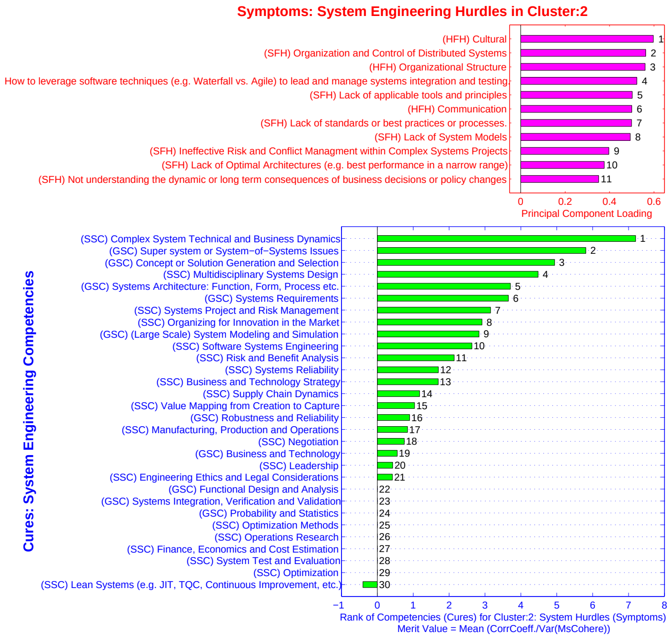


Figure 2-10: Ranking of System Engineering Skills (or Cures) for Cluster 2 Hurdles (or Symptoms).

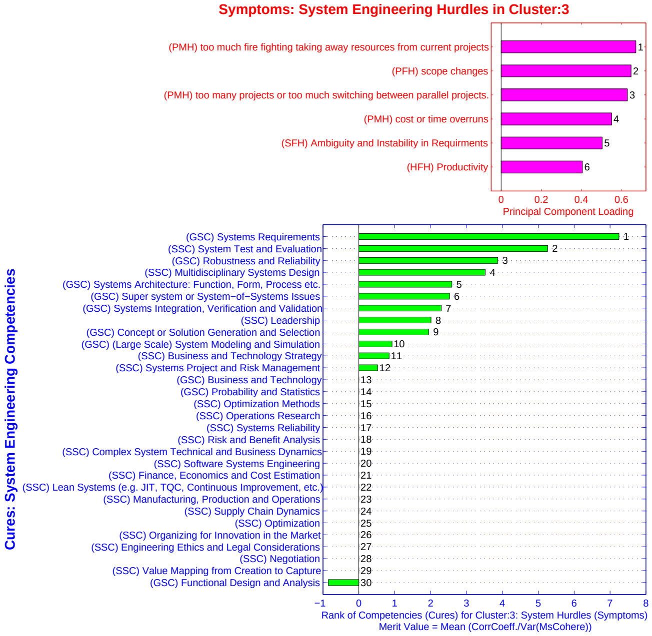


Figure 2-11: Ranking of System Engineering Skills (or Cures) for Cluster 3 Hurdles (or Symptoms).

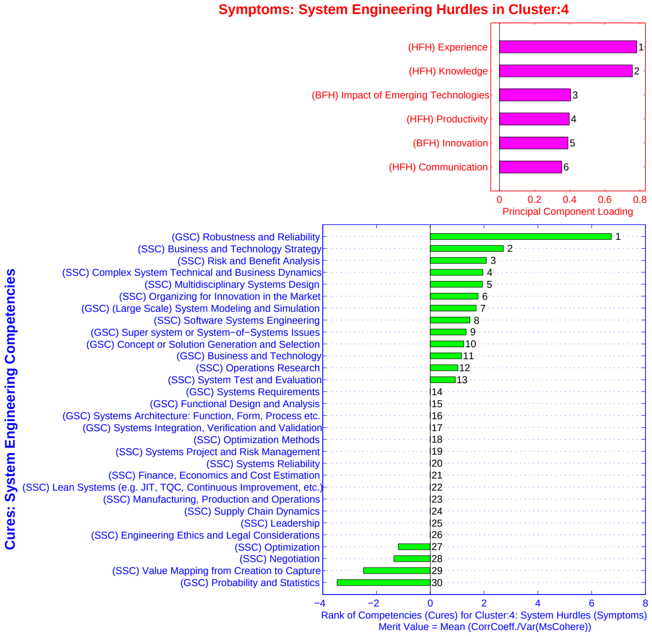


Figure 2-12: Ranking of System Engineering Skills (or Cures) for Cluster 4 Hurdles (or Symptoms).

- *Symptom: Extreme Sensitivity to and inability to cope with Ambiguity and Instability in requirements. Or alternatively, extreme emphasis on deriving perfect specs or intensively engaging the customer to review each item on a huge detailed list of specs*

Dealing with hurdles that arise in developing complex engineering systems is in some ways similar to diagnosing medical conditions that exhibit multiple sometimes overlapping symptoms. The medical field has reached sufficient maturity where it is often possible to fit a number of symptoms into a well known medical condition with treatment options that are agreed upon by a large number of practitioners to be the best available option currently available for that condition. By analogy it is reasonable to expect that we should be able to derive similarly useful tools when dealing with Engineering Systems that are many orders of magnitude less complex than the Human body [10].

The bottom line results given in Figures 2-9,2-10, 2-11 and 2-12 is an attempt to find such a framework based on more than 12000 years[11] of technical and managerial experience in developing Engineering Systems. The proper way to use this framework is to match all the observed symptoms to one of the four clusters by comparing them to the list at the top portion of the plots. If a good match is found, then one can select the most effective tools from the list of competencies as permitted by the available resources. For example, if the symptoms match Cluster 1 exactly, the interpretation is that the symptoms match a particular condition (i.e. Cluster 1) defined by about 80 professionals. In addition, selecting the highest ranked skills will meet with the least disagreement among 690 professionals. Now if there is an ill defined situation where very little information is available to choose the best approach, then this chapter gave ample evidence that one would do well to choose *Robustness and Reliability* because it is a top hitter on 3 out of 4 clusters. This study found other top hitters across the clusters such as *Complex System Technical and Business Dynamics.*

This framework is not perfect. For example, one can argue that the options given to the professionals are not clearly understandable or that different people understand them to have

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[10] The Human Body is not an Engineering System according to definitions introduced by Joel Moses [36]

[11] This is the area under the experience curve represented by histograms in figure 2-1. Like counting lines of code in software, it is used here because it is a very simple measure, and not necessarily the best.

different meanings. However, this framework is likely to remain useful until such time that a larger scale framework emerges that comes close to matching complex engineering system symptoms and cures.

Finally, this chapter justifies why the Robust Design framework was the most suitable compass for the main topic of this thesis: *Systems and Strategic Impact of the emergence of the ICPS technology*, because the issues of concern are an excellent match to the issues of Cluster 1 where *(GSC)Robustness and Reliability* is a highly ranked approach.

Chapter 3

Robust Design Evolution and Systems Impact of the ICPS

”A small leak can sink a great ship.”

- Benjamin Franklin

”It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change.”

- Charles Darwin

Franklin was primarily interested with Socio-Political issues of government and Darwin studied the evolution of biological organisms. Yet, their conclusions have a great deal in common with Engineering Systems where complexity affects robustness. If we drill a hole in a plank of wood, it continues to float. Yet a whole ship made of many components primarily out of wood is very sensitive to a small leak. Darwin’s quote is also very much in line with a conclusion of chapter 2 that optimal designs (e.g. strongest or most intelligent) tend toward ”brittleness” or low chances of survival. They only have to remain ”strong enough” or ”intelligent enough” when exposed to large variations in conditions during their life cycle. Like biological systems, the architecture of engineering systems evolve in the direction of adaptability or robustness to change. The reader can confirm this curious fact that in a large number of patents, including the ones referred to in this chapter, the stated motivation for the invention is typically to reduce the sensitivity that an earlier architecture or prior art is claimed to have to some critical factor or disturbance[1].

In the context of engine systems, the most significant factors are the environmental emission and efficiency regulations, fuel prices and the security concerns over reliance on foreign oil. By tracking technology, market and regulatory trends, Bandevadekar[37] expects that major architectural alternatives to the internal combustion engine (such as fuel cells) will not reach sufficient maturity in the near or medium term. The OEM's reaction to the changes is expected to be characterized as incremental architectural innovation. To comply with the known and expected "changes", Engine Systems are gaining complexity by the addition of more advanced or optimized components such as multi-mode combustion, multiple (or flex) fuel, variable geometry turbochargers, exhaust after treatment systems with regeneration, more complex injection profiles, variable valve actuation etc. The added complexity and component optimization tends to make the system brittle, but this is unacceptable as customers have come to expect the highest levels of robustness and reliability from their cars. One way to significantly improve the robust performance of internal combustion engines, with added complexities, is to use a fast and accurate combustion pressure sensor to close the loop around the combustion process. This leads to the following component and system level questions:

1. How has the architecture of the ICPS evolved to improve its Robust Performance as a component? Section 3.2 examines the architectural variation of these sensors based on information in patents.

2. What is the predicted architectural impact of the emerging ICPS on Engine Systems within the context of Robust Closed Loop Control of combustion? What are the Synergies and Conflicts between ICPS and other technology trends? Section 3.3 finds some answers by analyzing data from interviews, patents, Internet based survey and recent symposiums where various developers presented their ideas or progress on advanced engine control

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[1] Altshuller's TRIZ Laws of Evolution of Technological Systems (reported by Clausing and Fey [16]) is based on rigorous analysis of a large number of Patents. The Law of Flexibility: *Systems Evolve in the Direction of Increased Flexibility* is very much in line with this observation.

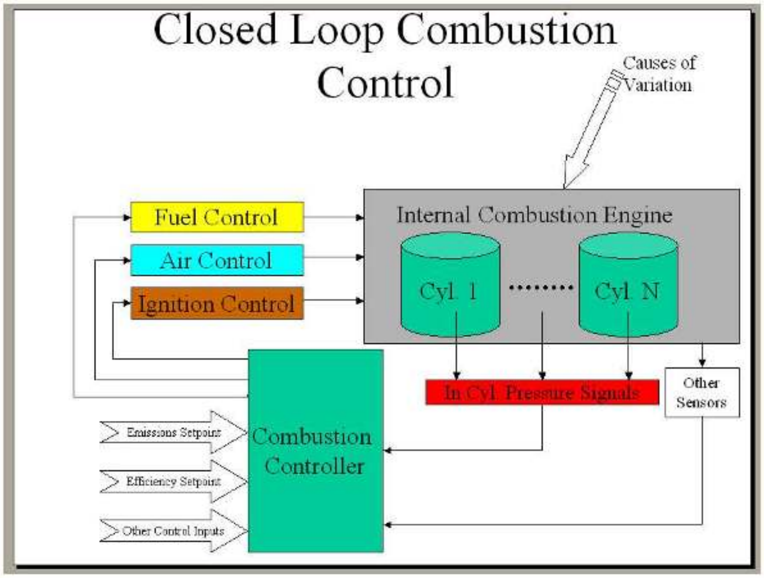


Figure 3-1: Using In-Cylinder Pressure signal to Close the Loop On Combustion.

using the ICPS.

Figure 3-1 gives the Robust Closed Loop Control context of this chapter, where the engine is supposed to deliver acceptable or good enough emission, efficiency and torque (or power) levels everywhere within the known bounds on external sources of variation that include:

- Fuel Types (Diesel, Gasoline, Bio-Fuels, Synthetic Fuels, Natural Gas or LPG
- Fuel Quality (e.g. purity, cetane number etc
- Combustion Modes (Diesel, HCCI, SI) and transition between them
- Environmental Temperature and Pressure
- Load Characteristics and Disturbances

Other sources of variation such as variable geometry position of the turbochargers are are either internal or external depending on the controls architecture, but must obviously be included in the Robust Control context.

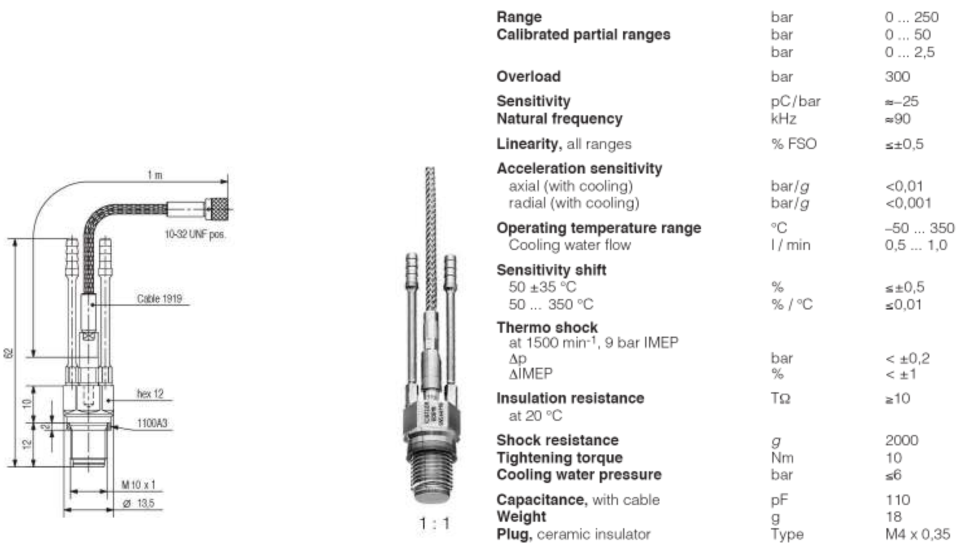
This chapter is based on open literature, an Internet-based survey done by the Robust Design Group at MIT, and interviews with experts on the topic of ICPS in the automotive industry. In some cases, the information is not from a published source or an identified individual. This was unavoidable as the OEM's or consulting outfits that do much of the advanced upfront engineering work for them, are not divulging any details. To illustrate the point, a press release from Beru mentions that there is a European OEM that will employ their pressure sensor in 2008 on a production engine. But they do not identify the OEM. Meanwhile, by tracking announcements (see section 1.2.2) we know that the OEM is most likely Audi or VW since Audi's design is based on the VW engine. So there are pieces of information that people are willing to share in a conversation that they would not be willing to put down in written or published form. In particular, the information in chapter 3.1 is not meant to be accurate as the author did not have access to proprietary spec sheets from the OEM's.

In his thesis at Chalmers University, Martin Larsson [5] gives an excellent theoretical overview of various types of combustion sensors as well as experimental comparison of their performance. Among the pressure sensors, he clearly favored the Piezoresitive sensor (section 3.2.2) over the Fibreoptic sensor (section 3.2.1). The reader is referred to that thesis for the basics of various types of sensing elements and balanced opinions based on experiments as to what sensor fits what application etc. So this chapter will focus on Robust Performance Requirements, Architectural Evolution of Various Types of ICPS and their Architectural Impact on Engine Systems.

3.1 The Requirements for ICPS

3.1.1 The Gold Standard on Performance (Accuracy and Precision)

The water cooled natural quartz based pressure sensors are expensive but as the data in Figure 3-2 for the Kistler 6061B shows, it remains accurate over a wide range of temperatures -40 ^{o}C to 350 ^{o}C. The practically negligible shift of only 0.01 percent/C is partially due to the properties of the natural crystal and partially due to water cooling that keeps the sensor tip



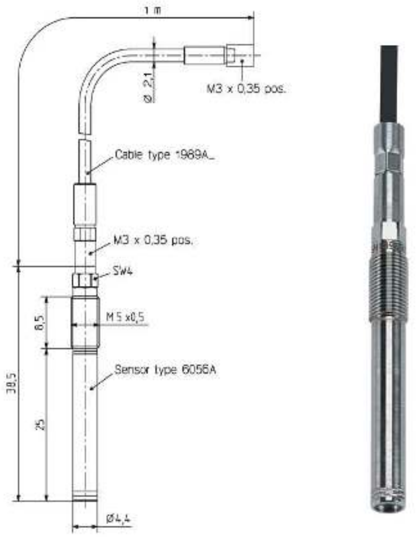
Range	bar	0 ... 250
Calibrated partial ranges	bar	0 ... 50
	bar	0 ... 2,5
Overload	bar	300
Sensitivity	pC/bar	≈–25
Natural frequency	kHz	≈90
Linearity, all ranges	% FSO	≤±0,5
Acceleration sensitivity		
axial (with cooling)	bar/*g*	<0,01
radial (with cooling)	bar/*g*	<0,001
Operating temperature range	°C	–50 ... 350
Cooling water flow	l / min	0,5 ... 1,0
Sensitivity shift		
50 ±35 °C	%	≤±0,5
50 ... 350 °C	% / °C	≤0,01
Thermo shock		
at 1500 min^{-1}, 9 bar IMEP		
Δp	bar	< ±0,2
ΔIMEP	%	< ±1
Insulation resistance	TΩ	≥10
at 20 °C		
Shock resistance	*g*	2000
Tightening torque	Nm	10
Cooling water pressure	bar	≤6
Capacitance, with cable	pF	110
Weight	g	18
Plug, ceramic insulator	Type	M4 x 0,35

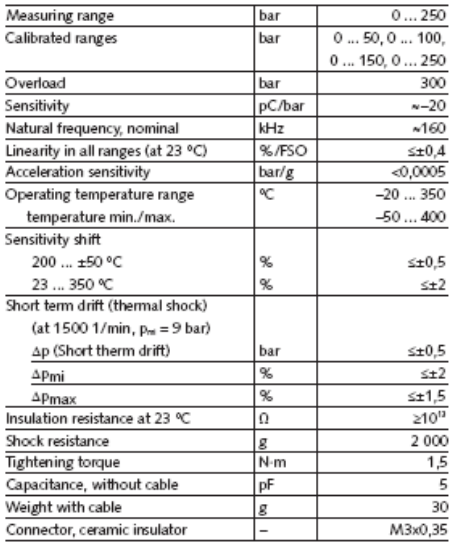
Figure 3-2: The natural quartz based Kistler ThemoComp Pressure Sensor 6061 B and its Technical Specification from Kistler Data Sheet 000-020m-09.95.

at the same temperature to overcome mechanical expansion of the sensing diaphragm interface with the crystal. Hence the cooling is not there to a avoid material damage. It is primarily to keep the measurement accurate withing a wide range of cylinder temperatures.

3.1.2 Robustness, Cost, Size and Dynamic Requirements

Actual requirements depend on the exact details of how the engine OEM plans to incorporate the sensors. However based on several RFQ's, a sensor manufacturer told the author that the performance is typically required to be within 2 % of the gold standard within a temperature range of upto about 260 C. Figure 3-3 shows the Kistler Sensor 6056 A with the associated data sheet that is intended for integration with the glow plugs. It is not clear whether this sensor is suitable for production engines or whether it serves as an on board R&D sensor. Assuming the design of this sensor reflects the worse case performance requirements from OEM's who want to close the loop on combustion, then this confirms that required magnitude of the shift within the temeprature range is indeed of the order of 2% as compared to the gold standard that is practically shift free. Another data point for the required temeprature range. Johnson[38] et. al.





Measuring range	bar	0 ... 250
Calibrated ranges	bar	0 ... 50, 0 ... 100, 0 ... 150, 0 ... 250
Overload	bar	300
Sensitivity	pC/bar	≈–20
Natural frequency, nominal	kHz	≈160
Linearity in all ranges (at 23 °C)	%/FSO	≤±0,4
Acceleration sensitivity	bar/g	<0,0005
Operating temperature range	°C	–20 ... 350
temperature min./max.		–50 ... 400
Sensitivity shift		
200 ... ±50 °C	%	≤±0,5
23 ... 350 °C	%	≤±2
Short term drift (thermal shock)		
(at 1500 1/min, p_{mi} = 9 bar)		
Δp (Short therm drift)	bar	≤±0,5
ΔPmi	%	≤±2
ΔPmax	%	≤±1,5
Insulation resistance at 23 °C	Ω	≥10^{13}
Shock resistance	g	2 000
Tightening torque	N·m	1,5
Capacitance, without cable	pF	5
Weight with cable	g	30
Connector, ceramic insulator	–	M3x0,35

Figure 3-3: The Kistler Pressure Sensor 6056 A for and its Technical Specification from Kistler designed to integrate with Glow Plugs via mechanical adaptors.

state the Maximum Mechatronic Temperature for Cylinder pressure sensing to be in the range 200 to 300 C. Hence, the robustness requirement of performance with respect to temperature variation given in the data sheet in figure 3-3, is to some extent verified by alyetrnative sources.

Now the sensor is exposed to a large number of pressure and temperature cycles over the life of the sensor. According to a supplier, the sensor is required to function for 150000 miles that translates to about 0.2 billion cycles while Heavy duty or large industrial engines will have a tougher requirement of 5 billion cycles. The sensor would then be required to not drift more than 3.5 % within 0.2 to 5 billion cycles.

Now, as will be explained later in section 3.3, production engines typically do not have enough room to bore another dedicated hole for the pressure probe. Hence there is a requirement to integrate the sensor with some other device. So the size requirement depends on for example whether the sensor is to be integrated with the spark plug, glow plug, injector valve etc. In an interview, the ideal diametric requirements for a direct measurement was stated to be 0.4 mm or 10 times narrower than the Kistler 6056 A in figure 3-3 that is intended for an indirect measurement where the sensor element is not in direct contact with the Cylinder pressure.

For cost, the author obtained three data points. A supplier that admitted that their sensor was lower performance gave an indication of US$ 12 that he expected would be reduced to US$ 6 in 5 to 10 years under OEM cost reduction pressure. Another supplier with a high performance sensor mentioned a price of US$ 20 and that his plant was being visited by teams of engineers from a particular OEM to see whether they could optimize the production process to reduce the cost to US$ 10. Another source in the US said that these sensors will never be employed for any price higher than US 5. Now since Audi, GM (Cadillac) and Honda have already decided to use this sensor on a production engine, then they are probably paying about US$ 20 for a good sensor. However as sales volumes pick up and as OEM's pressure suppliers to reduce costs, these sensor will probably reach the US$ 5 to US$ 10 target for a much broader appeal within 5 to 10 years.

Dynamic requirements again depend on the exact engine and the control technology and architecture employed. The fastest physical phenomena inside the Cylinders is the detonation (or knock) that typically manifests as a 5 to 15 KHz oscillation on the pressure signal for automotive engines. The larger the cylinder volume, the lower the knock frequency. So to be able to capture this effect, one needs a sensor bandwidth of theoretically at least 30 KHz[2] (2 x 15, if 15 KHz is the max knock frequency of engine) to avoid aliasing problems.

3.2 Architectural Variety of the ICPS

The key to the gold standard in performance of the water cooled Kistler in section 3.1.1 is that the properties of the natural quartz plus the water cooling of the tip assembly allows a very *Direct* and stable measure of the pressure inside the cylinder. *Direct* means that a small diaphragm is in direct contact with the pressure inside the cylinder where a sensing element directly senses the deformation of the diaphragm. In this sense, both Kistler sensors shown in Figures 3-2 and 3-3 are of the Direct type. Unfortunately, water cooling and natural or high quality synthetic crystals make the sensors prohibitively expensive. For example, a complete

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[2] In practice, higher than 30 KHz may provide more robust signal processing and better signal quality depending on how the signal is actually employed to control the combustion process.

advanced 6 cylinder engine may cost about US 3000 dollars whereas the natural crystal may cost around US 500 for each cylinder.

Examination of ICPS patents reveals that the biggest driving force behind Architectural Evolution of the ICPS has been the Robust Performance (or maintaining good enough accuracy with respect to large variation in temperature) and surviving a large number of harsh combustion cycles at a very low cost and in an easy to integrate package. Surviving is also in terms of performance degradation with the number of cycles or aging that is also a robustness issue. Easy integration refers to a physical package that does not cause a significant mechanical redesign of the core mechanical components of the engine such as cylinder heads or engine block and one that can integrate well mechanically and electronically with the engine control system. This is not an exhaustive list of all possible drivers, just the key drivers that have influenced the evolution at the component level. System level drivers and evolution are discussed later in section 3.3.

The response to the main drivers for the ICPS component has lead to the following branching of designs:

1. *Direct* versus *Indirect Sensing*. As explained above, the Direct method of sensing is closest to the measurand and therefore suffers least from temperature expansion effects and dynamic resonance[3] of mechanical components that connect the sensing diaphragm to the pressure sensing element. Unfortunately this puts the sensing element close to where the temperature variation is very large. Since the natural quartz is very expensive, other type of sensing elements (such as synthetic crystal) or sensing physics has to be used. There are several types of Direct sensors but the most serious contender regarding the Robust Performance and cost is the Fiber-Optic based Optrand sensor explained in more detail in section 3.2.1. *Direct* sensing is the most architecturally direct way to battle the Robust Performance requirement. However, most architectural innovations and currently available sensors fall into the *Indirect* sensing category where the designers have decided

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[3] Low Mechanical resonant frequencies limit the useful bandwidth of the sensor. For high bandwidth, the stiffness of the mechanical assembly must be high at low inertia.

to re-frame the problem to battle some 0ther issue than the large temperature range. The following list is ranked by the degree of *Indirectness* so that for example the last item is the most *Indirect*:

- Indirect Sensing of Pressure: by moving the sensing element away from the hot location and using some mechanical link to the location in the cylinder where the pressure acts upon. Here a cheaper sensing element (typically Piezo-resistive or Piezo-electric) can be used since the sensing element is only subjected to a fraction of the temperature range as in the Direct case.
- Sensing of another In-Cylinder property and correlating to In-Cylinder Pressure: Ion Sensing is a leading example with many supporters. Since the ion measurement is affected by the conductivity of the mixture in electrode gap that is affected by temperature, this type of sensor also has to deal with the drift issue. As discussed earlier in section 1.2.1, the In-Cylinder Pressure value is the *dominant* design variable for understanding and controlling combustion. Ion-Sensor suppliers therefore have the same burden of proof regarding the robust measurement of the pressure within the large temperature range.
- Model Based reconstruction of In-Cylinder Pressure: by using advanced controls and signal processing algorithms. Here the pressure waveform in the cylinder is reconstructed algorithmically by model based approaches that are either physics based (e.g. Kalman filters) or correlation based (e.g. Neural Networks). This has the potential for minimal architectural impact on the electronics and mechanical design of existing engine systems as one needs only the existing sensors plus possibly just one additional high quality sensor such as crank angle sensor. Unfortunately however, the typical situation is that the level of Controls technology applied to mature engineering systems lags the available control theory by about 30 years. So using advanced controls techniques alone to avoid the need to use any ICPS sensors altogether is a remote possibility, at least when it comes to mature organizations that develop engine systems.

2. Integration with another In-Cylinder Component: the lack of available room to drill a dedicated hole for the ICPS probe on production engines has driven various forms of integrated architectures where the ICPS is integrated with another In-Cylinder component such as the Spark Plug (for SI engines) and Glow Plugs (for Diesel engines). In addition, such integration can simplify the wiring and electronic connections to the control system. Suppliers typically have multiple patents and architectural variants for both Spark Plug and Glow Plug integrated designs. The BERU sensor in section 3.2.2 is an Integrated Glow Plug ICPS. The Denso sensor in section 3.2.3 is an integrated Spark Plug sensor. The Bosch ICPS in section 3.2.4 is architecturally very interesting because it is an integrated Injector Valve ICPS where the same Piezo element used for valve actuation is used for sensing pressure, representing a very simple and elegant solution to the problem of integration, but the Bosch 2008 catalog only includes an integrated glow plug so not clear when or if the integrated injector valve version will be available.

3.2.1 The OPTRAND Fiber-Optic Based Direct Sensor

The OPTRAND sensor is a serious contender for robust production grade *Direct* sensing of pressure inside the Cylinder. The sensing principle is shown on the left side of Figure 3-4. An LED shines a cone of light, via an optical fiber, on the inside surface of the sensing diaphragm. A Photo Diode detects the intensity of the reflected light from the diaphragm, via another fiber that sees the cone of reflected light. As the diaphragm moves to respond to pressure forces, the cross section of the two cones is a measure of the distance of the fibers from the diaphragm. So the intensity of the reflected light is a measure of the pressure force. The right side of Figure 3-4 shows an embodiment of the sensor tip. The electronic components (diodes, LED, signal processing) are packed on a quarter size circular disc that is connected to the other end of the fibers at a relatively cooler location around the engine away from the inside of the cylinder. The circuit produces a voltage signal that is proportional to the pressure applied to the diaphragm. Now the optical properties of the particular fibers selected are practically insensitive to temperature effects or electromagnetic interferences from other

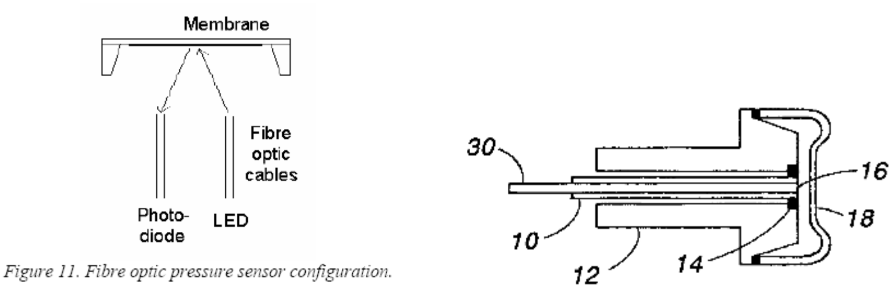

Figure 3-4: The fiber optic concept (left from Larsson's thesis [5]) and OPTRAND Sensor Tip (right from Wlodarczyk's US Patent [6]).

electronic components around the engine. The inventer Wlodarczyk told the author some of the early robustness challenges that had to be resolved architecturally:

1. Endurance of LED's at High Temperature: The interfaces between the fibers and LED and Photo Detectors were lossy, so the Diodes had to be run at high power to get enough signal. However running diodes at high power reduces their life considerably. By selecting the right fiber material and improving the quality of the optical and opto-electrical interfaces, the optical losses were reduced. This enabled the LEDS to run at low power and increased their endurance (hours) at high temperature.

2. Fading Diodes with time (aging) or Temperature Dependent Intensity from the diodes or variation in power supply to the electronics: The measurement system had to become insensitive to these variations in emission and detection of light intensity. This was resolved by having two photo detectors instead of one, where the additional detector was directly measuring the emitted light. The measurement was then based on the ratio of the measurement from the two photo detectors.

3. Fouling such as soot build up on the tip: this was taken care of by modifying the shape and properties of the diaphragm and the way it was integrated into the sensor by integrating the sensor tip in such a way that it still measured the pressure directly but it was shielded from soot build up.

4. Sealing: The fiber and the internal surfaces of the sensor had to be hermetically sealed from the combustion products over the life of the device. This was resolved by choosing the appropriate laser welding technique for attaching the diaphragm (tagged 18 in figure) to the sensor tip body (tagged 12 in figure).

Optrand's 2004 patent [6] explains that there are still offset and sensitivity errors due to fundamental material property differences (Poisson number and Young's modulus). For example, in Figure 3-4 it is possible to get differential expansion between the tip body (12) and diaphragm (18) so that the key distance between the pickup face (16) and the reflective inside surface of the diaphragm become sensitive to temperature.

Another problem is unit to unit variations and the adverse effect on light intensity due to sharp bends in the cable carrying the fibers from the electronics to the sensor tip. These issues were architecturally resolved in a 2007 patent by Wlodarczyk [7]. Figure 3-6 shows the evolved design in the form of an integrated glow plug sensor. The left of the figure shows the short rigid (tagged FIG 3A) and long cable version (tagged FIG 4) of the device. The electrical connector component (tagged 24 in FIG 3A, FIG 3B and FIG 4)also contains the electrical circuit that contains the LED, Photo detectors and signal processing circuitry that output a voltage that is proportional to the pressure. Other than integration with a glow plug that is a standard component on diesel engines, the key architectural difference with respect to robustness to temperature is that there are now three optical fibers at the sensors tip versus 2. The additional fiber is the Reference fiber that is pointed to another point inside the sensing diaphragm, such as near the circumference of the diaphragm. The Measurement fiber is pointed toward the center of diaphragm. The bundle of three fibers is shown in sub-figure FIG5 in Figure 3-5. The right side of the figure plots the signals that are returned by the Measurement and Reference Fibers as function of distance of the fibers from the diaphragm. The measured pressure signal is then based on the ratio of the measured voltage from Measurement fiber and the difference in the voltage of the two fibers. In this way, the pressure measurement is based on response of two points on the diaphragm alone and therefore not sensitive to differential expansion between the fiber assembly and the diaphragm. Since the Reference fiber is bundled

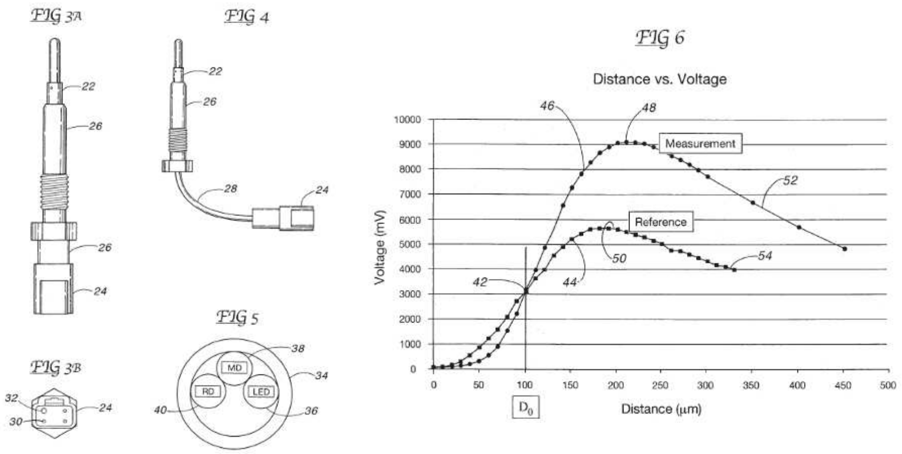

Figure 3-5: The 3 fiber version of the OPTRAND Sensor (left). Pressure measurement is now based on the relative sensitivity of the measure versus reference signals (right) [7]).

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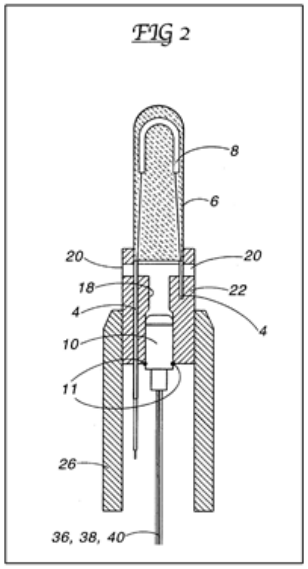
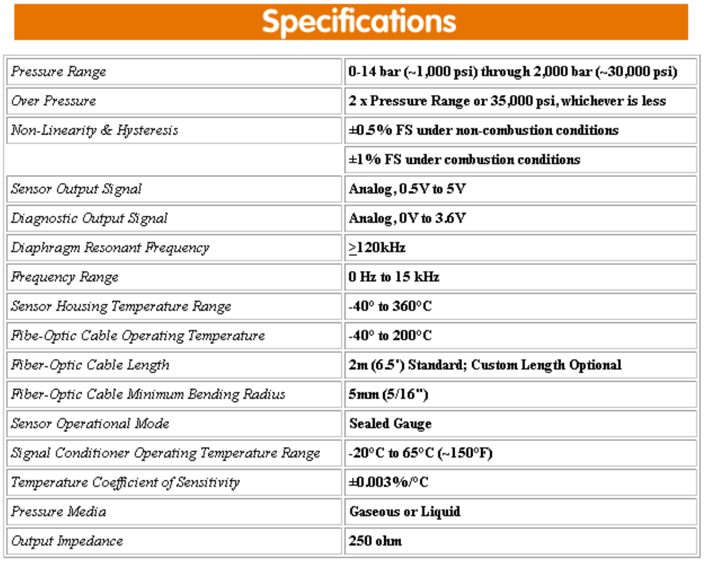
with the Measurement fiber, they will have close to identical bending patterns and hence the effect of bending on intensity is compensated.

To overcome unit to unit variation so that different sensors are matched exactly in their linear range, during assembly, as the fibers are inserted, the assembler is watching the live voltage signal returned by the two fibers and adjusts their exact positioning and the electrical gains such that the two curves cross at their most linear part of the curve (tagged 42 in the figure).

Figure 3-6 shows the integration details of the OPTRAND glow plug. The sensing ports (item 20) and the channel leading to the sensing diaphragm are designed in order to avoid build up of soot and other deposits that can affect proper operation within the life of the component. Wlodarczyk believes that his sensor is the most convenient for integration because the optical fibers are thin and very flexible and because the sensor tip is very narrow and has the potential to come closest to the 0.4 mm ideal requirement given in section 3.1.1. The right side of the figure gives the technical specification including a temperature sensitivity and range that matches the water cooled Kistler discussed in section 3.1.1.





Specifications

Pressure Range	**0-14 bar (~1,000 psi) through 2,000 bar (~30,000 psi)**
Over Pressure	**2 x Pressure Range or 35,000 psi, whichever is less**
Non-Linearity & Hysteresis	**±0.5% FS under non-combustion conditions**
	±1% FS under combustion conditions
Sensor Output Signal	**Analog, 0.5V to 5V**
Diagnostic Output Signal	**Analog, 0V to 3.6V**
Diaphragm Resonant Frequency	**≥120kHz**
Frequency Range	**0 Hz to 15 kHz**
Sensor Housing Temperature Range	**-40° to 360°C**
Fibe-Optic Cable Operating Temperature	**-40° to 200°C**
Fiber-Optic Cable Length	**2m (6.5') Standard; Custom Length Optional**
Fiber-Optic Cable Minimum Bending Radius	**5mm (5/16")**
Sensor Operational Mode	**Sealed Gauge**
Signal Conditioner Operating Temperature Range	**-20°C to 65°C (~150°F)**
Temperature Coefficient of Sensitivity	**±0.003%/°C**
Pressure Media	**Gaseous or Liquid**
Output Impedance	**250 ohm**

Figure 3-6: The Integrated Glow Plug from Wlodarczyk's US Patent[7] (left). Technical Specs from OPTRAND's web site (right).

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Houben et. Al.[8] from BERU (proponents of the Piezoresistive sensor) compared several In-Cylinder combustion sensing concepts. They rated the accuracy, stability of signal, output signal and static pressure measure of the optical concept as excellent. However they did not like the integrability of the sensor with the glow plug and hated the cost. But this was reported in 2004 before the 2007 OPTRAND integrated glow plug patent. A recent conclusion that was based on experimental comparison is from Martin Larsson [5] thesis in 2007. He found the Piezo-resistive (discussed in next section) sensor to be most like the Gold standard Kistler sensor in characteristics. He also found that the Piezo-resistive, optical and gasket type pressure sensors would all have negative characteristics but would all be suitable for closed loop control of combustion. Unfortunately, the determination of the robustness of combustion sensors was not a specific goal of Larsson's thesis so this conclusion is an indication but not watertight for the purpose of this thesis.

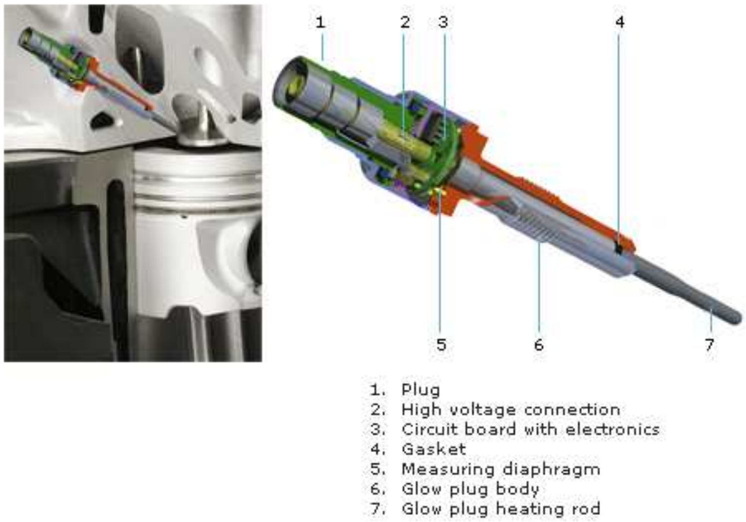

Figure 3-7: The Beru Integrated Glow Plug with Piezo-resistive sensing element moved to a cooler location in the Cylinder head.

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3.2.2 The BERU Integrated Glow Plug ICPS

From the cryptic company announcement, it may be concluded that the BERU sensor is the one selected for the Audi Q7 application described in section 1.2.2 and so may be one of the first to appear on a production engine and has the potential to dominate the European market at least initially.

Figure 3-7 shows how the BERU integrated Glow Plug sensor fits into the cylinder head. Note that the measuring diaphragm (tagged 5) is at to a cooler location outside the cylinder head casting. The sliding heater rod of the glow plug (tagged 7) is responsible for mechanically transferring the pressure force to the sensing diaphragm.

Figure 3-8 shows the measurement principle, the ASIC used for signal processing and the technical specification. Like the optical sensor, the BERU piezo-resistive sensor can measure static pressure and has low drift. The robustness performance at cost of the BERU sensor is due to the following architectural features:

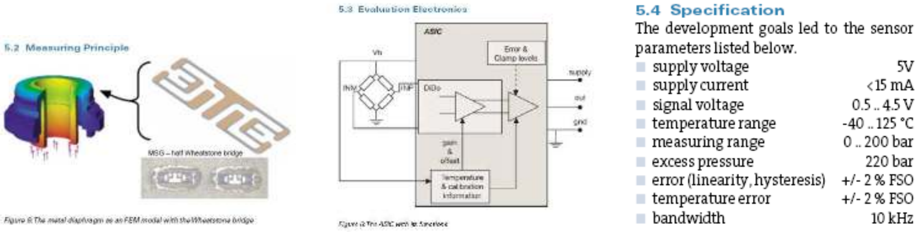
- The Piezo-resistive sensing element is a Micro-fused Strain Gage (mono-crystal silicon wire shown in Figure 3-8) that is hermetically sealed and has good linear characteristics. It is glass bonded to the steel sensing diaphragm and measures its strain.

- Since this measurement is based on strain in the steel diaphragm, it will be sensitive to its temperature dependent expansion. This was resolved as follows:

    1. *Indirect* Measurement: Location of the sensor element just outside the cylinder head sees less temperature range than when the sensor is closer to the combustion chamber.
    2. The sensing element lends itself to easy integration with an ASIC where temperature characteristics may be filtered or corrected. Reference [8] mentions that the temperature signal is coming from the sensing diaphragm. So we may assume that the +/-2 % is mainly due to sensing the temperature of the diaphragm, for if the temperature of the diaphragm was known perfectly, most of the temeprature dependent expansion characteritic could be corrected for in the ASIC.

- The mechanical design of the Gasket/Seal and the components it touches has to be special in that it must have low friction to not hamper the dynamic translation of the pressure force and yet must remain tight enough to seal and protect the rest of the sensor from combustion products. The joint BERU/Texas Instrument patent [39] describes an evolution of the seal in the form of a ”bellows-like” design that make the sealing function (or the friction) insensitive to pressure changes.

Houben et. Al.[8] explain that by choosing the mechanical dynamic response of the heating rod (item 7 in Figure 3-7, they can mechanically tune the bandwidth of the sensor. They explain this as an advantage. The author suspects that they are trying to explain away a disadvantage as an advantage. It is hard to accept that one would throw away the possibility of filtering the signal in the available ASIC component (a reliable and cheap endeavor), and instead purposely rely on mechanically tuning (i.e. redesigning) the component to condition the signal. For signal to noise issues, it is best to have the highest stiffness and lightest design



5.4 Specification

The development goals led to the sensor parameters listed below.

supply voltage	5V
supply current	<15 mA
signal voltage	0.5 .. 4.5 V
temperature range	-40 .. 125 °C
measuring range	0 .. 200 bar
excess pressure	220 bar
error (linearity, hysteresis)	+/- 2 % FSO
temperature error	+/- 2 % FSO
bandwidth	10 kHz

Figure 3-8: The Measurement Principle, ASIC and Technical Specification of the Beru Integrated Glow Plug Sensor (copied from [8]).

to have the highest possible mechanical bandwidth followed by sampling and filtering the signal in the ASIC component.

An interesting dynamic comparison of the Piezo-resistive versus the Optical sensor of the previous section is that with the former, the bandwidth is limited by the sensing path to the sensing element, whereas with the Optical sensor, the bandwidth is limited by the opto-electric conversion after the physical sensing. If in future, it turns out that very high bandwidth is a practical advantage, then the Optical sensor will have an edge. However, the cost advantage of the Piezo-resistive combined with good enough sensor characteristics may enable it to dominate the market.

3.2.3 Denso Integrated (Spark and Glowplug) Combustion Pressure Sensor

Patents by Watarai et. Al. [9] and Yorita et. Al. [10] describe Denso's Piezoelectric based combustion pressure sensing concept that can be integrated with the spark plug or the glow plug. Figure 3-9 shows the integrated spark plug concept. Denso has also opted for the *Indirect* sensing so the Piezoelectric sensing element, is at a cooler location. The pressure is then transferred via a mechanical assembly to the sensing element. The Denso patents describe the following robust design features:

- *Indirect* Sensing: Similar to the Beru sensor, moving the sensing element away from the combustion chamber reduces the temperature range that the sensing element is exposed to.

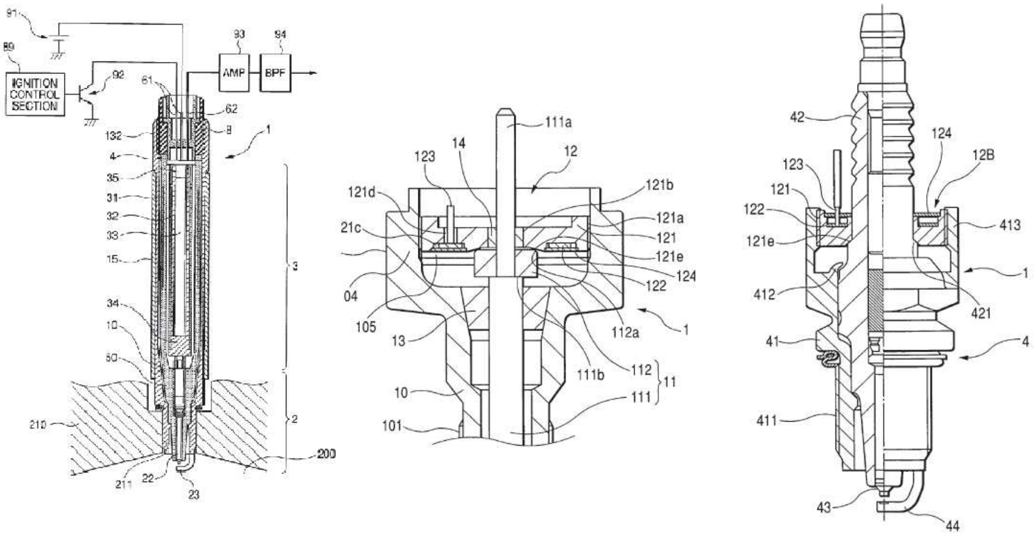


Figure 3-9: The Denso Pressure Sensing Spark Plug from US Patents [9, 10].

- *Bending* versus compressing the sensor: Instead of a full surface contact between the mechanical assembly and the sensor, the pressure force is first mechanically transfered to a bending member so that the sensor senses the bending and not a direct compressive force. The inventors claim that this reduces the unit to unit variation of sensing characteristics and temperature sensitivity. Otherwise a perfect surface fit would be required at the mechanical interface with the sensor using high precision manufacturing (expensive) or excessive compressive pre-loading of the interface.

- *Damping* : Unlike BERU, the Denso patent [10] identifies the dynamics of the mechanical assembly that translates the pressure force from inside the combustion chamber to the sensing element as a robustness concern, rather than a structural solution to enhance the quality of the signal. For example, the inertia of the mechanical assembly can pick up engine vibrations or g-shocks that can show up in the measurement. In addition, this can affect the pressure measurement in different ways depending on the temperature. Denso claims to solve this by adding a purpose made damping element that isolates the engine vibrations from the sensing element.

3.2.4 The Bosch Integrated Injector Valve Sensor

Bosch has several ICPS patents such as the piezo-resistive sensor by Moelkner et. Al. [40]. This sensor is interesting because it appears to be a *Direct* sensor where the sensing diaphragm is in the combustion chamber, on the back side of which is a thin MEMS thin strip containing strip Piezo-resistive sensor. The patent is however very cryptic and does not clarify the most interesting issue of how they propose to solve the temperature sensitivity of the piezo-resistive strip.

Bosch's other patent by Simon et. Al. [41] is shown in figure 3-10. Here the Piezo-electric element that is used to actuate the fuel injector, is also used to sense the cylinder pressure. This concept of integrating sensing with injection is very powerful because the combustion mode that most benefits from pressure sensing (i.e Homogeneous Charge Compression Ignition) needs neither a spark plug nor a glow plug. But an internal combustion engine cannot function without fuel. In a recent IAV Symposium, Mehlfeldt from Daimler and Raupach from Bosch gave a presentation on "Possibilities and Limits of the Utilization of Inherent Sensor Properties of Piezoelectric Actuators". They explained that the piezo-electric properties that are suitable for actuation (soft) are very different to the properties that are suitable for robust sensing (hard). So it is not clear, how the same element can be used for both functions. However, if a piezo-electric element can be developed with dual properties for robust actuation and sensing, then this concept is likely to be very powerful as it has a potential to simplify the overall engine control architecture by integrating the function of injection, ignition and sensing into one component.

3.2.5 Other Sensors

The objective of this chapter is not to give an exhaustive treatment of all the ICPS patents. There are other ICPS architectures. The idea for a production engine ICPS started in the early 80's. The 1983 patent by Kleinschmidt et. Al.[42] is an example of an early piezo-electric indirect measurement concept. Major OEM's or their key suppliers such as BERU, Bosch, Denso, Delphi and Siemens all have a number of ICPS patents that typically span the range of

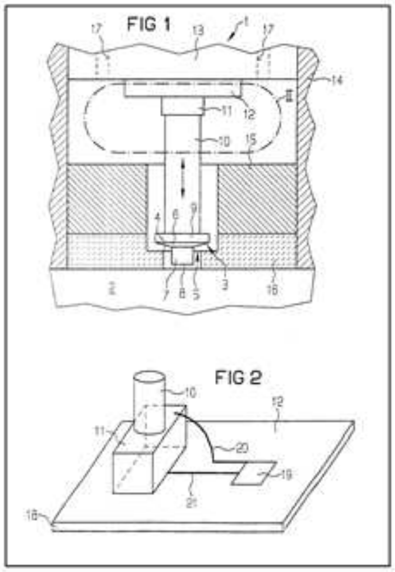


Figure 3-10: The Bosch Integrated Injector Valve Pressure Sensor

integration concepts given above. For example, Ford et. Al. [43] have an integrated spark plug concept that senses pressure by the strain in the plug shell.

Another example, according to a report in the Electronic Weekly [44], "Toyota claims it has the worlds first mass produced combustion chamber pressure sensor...", where they fitted the sensor to Toyota Carina E only available in Japan. It is odd that if Toyota already had a robust production ICPS at a low cost in 1994, normal expectation would be that their engines would all be fitted with this sensor and the emergence of the ICPS would be old news by now. Perhaps their focus on their disruptive Hybrid technology had higher priority than improving the technology of a mature engine system.

In his thesis Larsson[5] also tested a gasket type sensor that is on the cheap end of the spectrum but concluded that it was good enough for engine control, although he was not evaluating the sensors according to their robust design: i.e their insensitivity to key factors such as temperature or vibration.

Kroetz et. Al [45] report new developments in the preparation and application of Silicon Carbide(SiC) on Silicon (Si). This solves the dilemma of micro-machined sensors that also exhibit good thermal, electrical and chemical properties so that microchip based sensors will become suitable for *Direct* sensing of pressure in the combustion chamber. In particular they report data that show very flat response or robustness to aging, pressure and temperature. Chen and Mehregany [46] tested a SiC capacitative ICPS and showed worse case nonlinearity of 2.4% and temperature coefficient of 0.05% up to 574 C.

Wendeker et. Al. [47] use a fiber optic element in a different way than the OPTRAND sensor discussed in section 3.2.1. Here the cylinder pressure force affects the interferometric transmission of the fiber that. An interferometric decoder is then used to output a pressure signal.

With the increasing availability of on engine computer processing power and capacity, Model-Based or Virtual Sensing becomes increasingly viable. The best way to utilize models, whether they are physics-based (e.g. Kalman filters) or correlation-based (e.g. Neural Network) has been to use a very good quality or accurate signal and infer other properties or states that are not directly measured. The author found no example where a virtual sensor was the primary element of a robust solution, i.e. robust solutions that rely purely on models or models combined with very low quality sensors. But there are many examples of robust solutions that combine model based techniques with at least one high quality sensor. Assuming a good quality Cylinder Pressure Sensor value is available, there are references [35, 32] on how model-based techniques can be used for virtual sensing of other hard or expensive to obtain signals. Timoney et. Al [48] give a semi-empirical model that takes the Cylinder pressure value as its primary input and outputs the NOx level that in tests showed a remarkably high degree of fit ($R^2 > 98\%$) with the reference measured NOx value for a light and heavy duty diesel engine. Now why use a model, when you can measure? Well, it is cheaper and can give transient output so that for example, one could use this type of model for controlling the individual cylinder emission levels directly.

Thompson et. Al. [49] give an example of how they used a Neural Network based model to predict Hydrocarbon, CO, CO2, NOx, HC within a precision of 5%, based on signals that are typically available around the engine. The least accurate prediction of the output was engine torque. But torque can be very accurately demtermined by the cylinder pressure signal versus the crank angle, so it is not a stretch to think that better prediction of emission levels would be possible by combining modelling with a robust ICPS.

3.3 Systems Impact of the ICPS

There is a lot of scattered information on ICPS technology on specific aspects of engine control. For example, the majority of the ICPS patents referenced earlier also describe a few benefits of the ICPS as the inventors see it. In addition there is a number of patents, papers and text books that cover how ICPS is to be employed for a particular purpose However the information is scattered in a large publication space. This section uses expert input via interviews and an Internet based survey to extracts a high level overview of the impact of the ICPS and its synergies or conflicts with other technologies.

3.3.1 Why Robust Closed Loop Control of In-Cylinder Pressure?

Engine systems have evolved as a response to continuous cost and regulatory pressures. The evolution has involved both component optimization to mainly reduce cost or performance as well as architectural changes to improve the emission and efficiency. The general trend has been increased complexity and a larger number highly optimized individual components or subsystems. The increased sensitivity of engines has lead to symptoms that are similar to the generic list of symptoms given in section 2.1.2. For example, it can take an OEM 5 years to a common rail system to an engine, where a large portion of the cost and time is in testing, verification and validation.

The performance sensitivity of engines is already on the radar screen of regulatory organizations. Zachariadis [50] reported on the tendency to ”tune” engine performance to the exact testing cycle used by regulatory bodies for qualification. The discrepancy between test and on-road Fuel economy was as much 20 % in Germany, France and UK in some years. The fact that the International Energy Agency is getting smarter about performance sensitivity, implies that it will be increasingly difficult to ”perfectly tune” the engine to an exact qualification test cycle, at the expense of poor performance at other points that are not included in qualification.

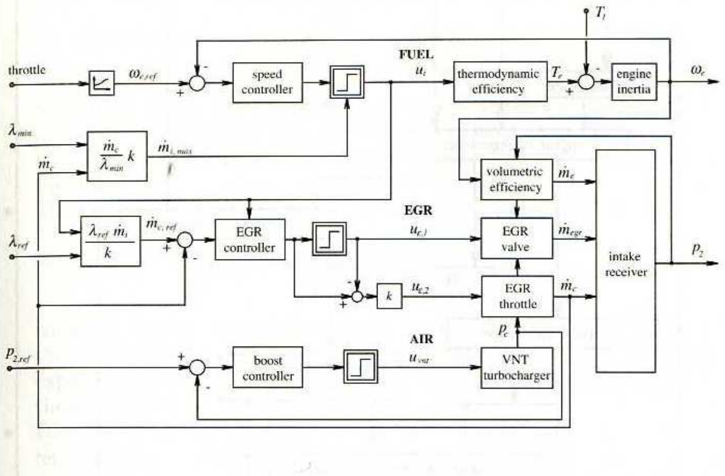


Fig. 1.9. Basic Diesel engine control system structure, variables defined in Fig. 1.8.

Figure 3-11: Diesel Control Architecture. (from Guzzella and Onder [11]).

All engines today can claim that they have in one way or another closed the loop on the combustion. Guzzella and Onder [11] describe the architecture of basic Diesel and SI engine control system. The former is shown in figure 3-11. The figure shows three feedback loops to control Fuel, Air (Boost Pressure) and EGR (Exhaust Gas Recirculation). In practice, the classical control structures rely heavily on Feedforward controllers. These are in the form of lookup tables or equations, determined by extensive testing at many points in the operational envelope. The Feedforward controllers do not affect stability and allow the Feedback loops to be lightly stressed, so that one can in fact use cheap sensors and decouple the control loops into separate concerns as shown. The issue is that as the engine complexity increases to meet tighter requirements, it becomes increasingly difficult and expensive to solve the problem by using finer lookup tables because the dimension of the problem grows exponentially. Even if super fine resolution and highly dimensional tables were possible, there is a limit to the robustness of the correlation between cheaper sensors outside the cylinder and the exact details of the combustion process inside the cylinder that determines efficiency and emission.

Unlike lookup tables used in feedforward controllers, the real physics that governs the combustion process at run time on a production engine is not fixed and less controlled than in

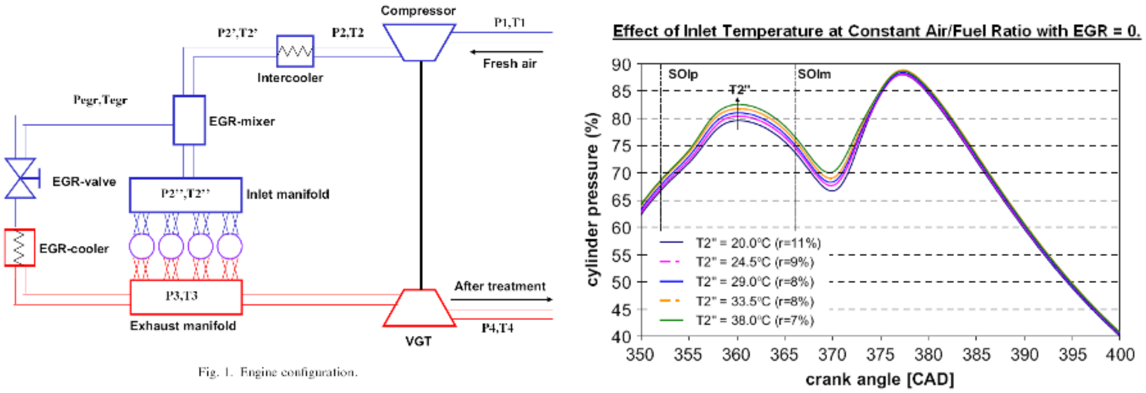


Figure 3-12: The Engine Configuration Tested by Meiboom et. Al. [12]. The plot shows the measured effect of Inlet Temperature (T2) on Cylinder Pressure at Zero EGR for a constant Air/Fuel ratio.

the test cells used to derive the tables. Since the physics is very sensitive to a large number of factors, the lookup tables grow exponentially to accommodate the increasing engine complexity. For example, aging of the components, temperature, pressure or fuel quality have a significant impact and have to be accounted for in some way. ICPS enables higher gain feedback controllers to control the combustion process more tightly without having to worry about the exhaustive combination of factors that the engine is likely to see in its lifetime.

3.3.2 Technical Description of the Problem

The report by Maiboom et.al.[12] provides an excellent backdrop for a technical understanding of the robustness problem in controlling internal combustion engines. Figure 3-12 shows the Diesel Engine with Variable Geometry Turbocharger (VGT) configuration that they tested to identify the best control strategy for Exhaust Gas Recirculation (EGR). They employed staged combustion, i.e. used a Pilot as well as a Main Injection event in each cycle. The right side of the figure plots the In-Cylinder pressure trace as a function of Inlet Manifold temperature for constant Air/Fuel ratio. The traces show that the Main combustion event after SOI (Start of Injection) is more or less insensitive to temperature, whereas the Pilot Combustion event shows some visible sensitivity to temperature. These traces are for zero recirculation, i.e. the EGR

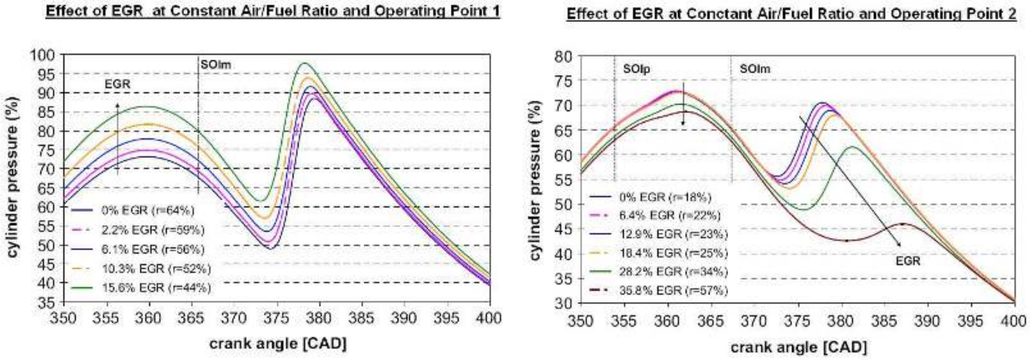


Figure 3-13: The Effect of EGR on Combustion Pressure at two operating points. (Copied from Meiboom et. Al. [12]).

valve is closed at a fixed operating point defined by Engine Speed, Rail Pressure, Pilot Injection Quantity, Main Injection Quantity, SOI Pilot, SOI Main, Manifold Pressure and IMEP.

However, it turns out that the situation is very sensitive to the EGR Valve position. Left side of figure 3-13 is the measured traces for the same operating point for different values of EGR. Here both the Pilot and Main combustion events are very significantly influenced by the EGR valve, although the Pilot event is still more sensitive. The right side of the figure shows what happens at a different operating point. Here the situation is reversed and the Main Combustion event is visibly a lot more sensitive to the effect of EGR valve position. Even more interesting is that the sensitivity to EGR changes direction from one to the next operating point, i.e. at the first operating point, an increase in EGR tends to increase cylinder pressure whereas at the second operating operating this effect is reversed. Note that these pressure traces are not fixed. For example, component wear or modifying the strategy for controlling the boost pressure will significantly change the traces. Even if there is no wear or change in boost control, there is no guarantee of an even distribution of recirculated gas between different cylinders. So, effectively each cylinder is running at a different EGR ratio. Furthermore, there are other significant sources of variation, such as environmental pressure, temperature, fuel type (in case of multi-fuel engines), fuel quality,cylinder-to-cylinder variation, and even seemingly remote effects such as the increasing congestion in traffic. This example illustrates the key point that:

- As engine architectures become complexer to respond to regulatory efficiency and emission regulations, there emerges higher dimensional and more sensitive system level behavior. This increases the need for Robust Closed Loop Control of Combustion.

The main purpose of the engine is to reliably deliver the required torque while maintaining acceptable efficiency (i.e. Fuel Consumption) and emission (i.e. NOx, CO, HC, PM etc.) levels within the normal expected variation in influencing factors. Note the word "optimal" was purposely missing from this explanation. Torque and efficiency are directly related to the ICPS trace. As explained earlier in section 1.2.1, there are numerous publications (e.g. Guzzella and Onder [11]) that show that one can easily relate the combustion pressure to heat release rate and emissions produced at the source inside the cylinder. Since the ICPS signal is a measure of Torque, Efficiency and Emission levels, then the combustion robustness problem can be simply stated as follows:

- The Combustion Robustness Problem: the Combustion Pressure Trace of Each Individual Cylinder is Sensitive to Unit-to-Unit, Cycle-to-Cycle, Fuel, Environmental, Wear, Operating Point and Complexity variations.

Carlucci st. al.[51] is another source that illustrates the robustness problem. They showed the combustion sensitivity of a dual-fuel diesel-natural gas engine to operating point, injection pressure and injected quantity. The above statement on the problem has a *detection* corollary:

- The Combustion Anomaly Detection: Combustion Anomalies show up on the Combustion Pressure Trace[4]

Internal combustion engines are mature systems. Their core mechanical architectures are already highly evolved. See for example the robust design evolution of Engine Cylinder Heads

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[4] As discussed earlier, the combustion pressure variable is the dominant variable for combustion. This does not imply that alternative sensors cannot detect combustion anomalies. However, this does imply that alternative sensors have to show a robust correlation to the combustion pressure trace or its features.

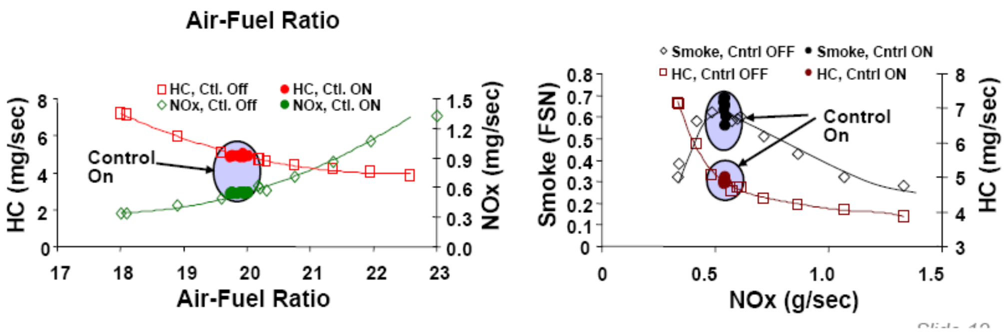

Figure 3-14: Purpose of closing the loop on combustion is to reduce the dispersion of Smoke, HC, Air/Fuel Ratio and NOx etc. into a small beneficial target region.

reported by Gomez[19]. The maturity of the mechanical design of the core implies that further optimizing the material properties, tolerances or minor mechanical improvement of the engine core components (e.g. the Cylinder Head, Engine Block, Crank Shaft etc.) are in isolation not the best or easiest way to meet the ever tightening emission, efficiency and safety requirements. Instead, the trend is to add complexity by optimizing or adding new subsystems or components such as Variable Geometry or Multistage Turbochargers, EGR, Complex Injection Profiles, New Combustion Modes (HCCI, PCCI), Diesel Particulate Filter etc. This gives rise to the robustness problem that was technically described above. An emerging trend to resolve this is by closing the loop on the combustion of individual cylinders and ensuring that it tracks a reference or target profile:

- The Robust combustions Control Solution: Maintains the Combustion Pressure Trace of Each Cylinder Acceptably Close to a (variable)Reference or Target While the Engine is Subjected to Variation in Influencing Factors Within Expected Bounds.

John Pinson's[52] presentation at the DEER conference in Detroit is an excellent example of looking at the combustion problem from a robustness perspective. He focused the PCCI (Premixed Charge compression Ignition) combustion mode of Diesel Engines. He listed the major sources of variation responsible for the "dispersion" in emission and noise levels: Mass Air Flow Sensor, Injector Variability, Compression Ratio, EGR Distribution, Fuel Quality (Cetane), Environmental Factors and Wear. Figure 3-14 shows that by closing the loop on the combustion pressure, he was able to significantly reduce the dispersion of NOx, Smoke, Air/Fuel Ratio, HC (shown with hollow data markers) onto a small target area (shown with solid data markers).

There are several detailed variants of combustion control using the combustion pressure sensor in patents and technical publications. The recent majority are focused on the new combustion modes of interest: HCCI (Homogeneous Charge compression Ignition) and PCCI (Premixed Charge Compression Ignition) combustion modes. These modes are tougher to control than the classical Spark Ignited gasoline or Diesel engine because the combustion starts spontaneously in various locations in the combustion chamber without directly triggering the combustion by a spark or an injection event. Bengtsson et. al. [53] compare various combustion parameter candidates to close the loop on CA50 (Crank Angle at 50% Combustion) for HCCI combustion. Lee et. al. [54] do a similar comparative study for closing the loop on the SOC (Start of Combustion) for a Diesel engine that is classically open loop controlled by the injection events.

Recent patents by GM[55, 56], Caterpillar[57, 58], Bosch[59], Mitsubishi Heavy Industries (MHI)[60], Honda[61] and Ricardo[62] are but a few recent example architectures that the patent holders may use to robustly close the loop on combustion using the ICPS. These patents use different terminologies, but without exception, point to overcoming the sensitivity of the combustion process in engines, in line with the *Combustion Robustness Problem*, *Combustion Anomaly Detection* and *Robust Combustion Control Solution* statements of this section.

3.3.3 System Architectural Benefits, Synergies, Conflicts and Hurdles

The ICPS component and engine control patents referenced in this thesis describe the problem with the prior art in terms of their sensitivity or shortcomings, followed by describing a solution that overcomes the problems. So by picking a large enough pool of relevant patents one can extract the expected system architectural benefits of the ICPS technology, together with how it may synergyize or conflict with other technologies. Unfortunately, this approach can lead to very large lists of items, without an evaluation of their relative importance. The author attempted to resolve this in two steps:

1. Step 1: Interview with 4 experts to make a short list. The 4 experts had the following job functions: Engine System Engineer (Woodward), ICPS component Developer and Business Owner (OPTRAND), Engine Component Sales (Siemens), retired Engine R+D Manager (Arvin Merritor) and Exhaust System R+D Manager(Eaton).

2. Step 2: Internet-based survey sent to other experts to estimate the importance of items in the above short list.

The second step was not as successful as the author had hoped as only 21 experts completed the Internet-based survey in contrast to the 690 respondents from a wide range of backgrounds that completed the CSU Survey reported in section 2.2. The author identified the following simple reasons for the low response, although there may have been deeper or more complex reasons:

1. Inability to recruit high to mid level directors at engine OEM's, engine system suppliers, or consulting groups to push the survey through their organization. They obviously had more urgent issues to attend to. There was also not enough energy or time left to peruse them.

2. Some well known experts that are well connected to the engine industry were extremely skeptical any information can come from a survey.

3. Robust Design Problem! It turned out that many companies block Java content in their Internet access. For example, people at Eaton and Bosch reported that they were unable to complete the survey in the office. We initially decided to use Java for its more optimal features in recording user interaction. However, this solution was not robust to the interaction modes allowed at the targeted companies.

Hence the list of items that describe the Benefits, Synergy, Conflicts and Hurdles are reliable because they are extracted from a large pool of patents and reviewed by experts. However, the rating of the items based on the survey results is only an indication because 21 data points is not large enough to run meaningful cluster analysis to find the main clusters of opinions etc. Furthermore, only 11 people supplied a clearly identifiable email address so the number of unique individuals that responded is uncertain between 11 and 21.

The background profile of the 21 respondents were:

- 9 people had a technical background.
- 7 people had a joint technical/business (or arts) background.
- 3 people had a business or social science background.
- 2 people had other background.

The market segment profile of the 21 respondents were:

- 7 people worked in the On-Highway.
- 6 people worked in at least 2 market segments.
- 4 people worked in the Off-Highway segment.
- 2 people worked in the Power Generation segment.
- 1 person worked in the Environmental Policy segment.
- 1 person worked in other segment.

The interest profile of the 21 respondents were:

- 5 people were primarily interested in the Environmental and Policy Aspect of Engine Systems.
- 10 people were primarily interested in the Technology Aspect of Engine Systems.
- 2 people were primarily interested in the Business Aspect of Engine Systems.
- 4 people were primarily interested in Other Aspects.

Eight respondents made original contributions in the areas of Air Control, Ignition Control, Exhaust Control, Control Algorithms and Systems Integration. They were asked how long it took before their contribution was copied or diffused into another domain. The average of their inputs was just over 4 years.

Eight respondents said that they modified their own engines. Three of these did the their own scheduled maintenance and the rest actually modified the Air, Fuel Ignition or the Exhaust path.

In the following sections, the most important items are emphasized with the number of votes added in brackets.

Summary of Benefits

What are the key benefits of Robust Closed Loop Control of Internal Combustion Engines using ICPS?

- *Better Cylinder-to-Cylinder Balancing(9)*
- *Reducing Cycle-to-Cycle Variation in Combustion in Each Cylinder(8)*
- *Reducing Emissions (NOx, Greenhouse Gases, Unburnt Hydrocarbons etc.)(7)*
- Detection and Avoidance of Misfires(7)
- Detection and Avoidance of Engine Knock(6)
- Improving Efficiency (e.g. Fuel Consumption)(5)
- Faster Time to Market (i.e. cost and time benefits)(4)
- Reducing Engine Noise(4)
- Easier Calibration(3)

Application Domain

What automotive area is going to benefit most from in-cylinder pressure measurement? What is the Primary Core competency required for this application?

- *Diesel + HCCI*
  - *System Integration (6)*
  - *Innovative Technology (5)*
- Gasoline + HCCI
  - System Integration (2)
  - Innovative Technology (2)

Synergy with other technologies or components

What other key technologies need to be utilized or co-developed to take full advantage of the emerging ICPS technologies?

- *System Integration (7)*
  - Better Communication/Bus Protocols
  - More Optimized Interaction or Joint Optimization of Components(2)
  - *Architectures that are Inherently Insensitive to Adverse Component Interactions (3)*
- Ignition Control(7)
  - Laser Ignition
  - Spark Ignition
  - *Direct or Indirect Control of Start of Combustion(2)*
  - Direct or Indirect Control of Middle of Combustion
  - Direct or Indirect Control of End of Combustion

- *Fuel Control(6)*
  - Variable Valve Actuation and Timing
  - Piezo-electric Valves
  - *Multiple/Tailored Injection Pulses(3)*
- Control Algorithms (5)
  - Better Signal Processing, Diagnostics and Prognostics(3)
  - Better Controllers that need little or no adjustment during engine life
  - Better Controllers that are tuned for specific engine conditions
- Air Control
  - Variable Valve Actuation and Timing
  - (Variable Geometry) Turbo Charger/Super Charger
  - Exhaust Gas Recirculation
- Electronics Hardware
  - Higher Temperature Ratings
  - More Compact Designs
  - Faster Computations e.g. Faster CPU's or FPGA's
  - Modular Hardware Design
- Exhaust Control
  - Better Catalysts
  - Better Filters/Traps
  - Better control of Pressure, Temperature and Gas Composition into the Exhaust Manifold
  - Better Exhaust Sensors

3.3.4 Conflict with other Technologies or Components

Here is a list of potential conflicts with the ICPS as can be deduced from the patent and other published literature. Note that a *conflict* need not necessarily be decided in favor of the ICPS. In order to prevail, ICPS has to replace components that are more mature and typically at a very low cost stage of their life cycle. So ICPS can either displace the following items, or can be displaced by incremental improvements in them.

- MAF, MAP, MAT, A/F ratio, Ion: Mass Airflow, Manifold Pressure, Manifold Temperature, Air/Fuel Ratio and Ion Sensors: The primary purpose for these sensors is to estimate the conditions in the cylinder and the parameters of the resulting combustion process. Since the majority of the combustion variables can be deduced from the In-Cylinder Pressure Trace, then it may render one or more of these sensors obsolete.

- Knock Vibration Sensor: These sensors can pick high frequency vibration resulting from engine knock (or detonation). However, the knock information is also contained in the ICPS trace from a high bandwidth sensor.

- Misfire Detection via the Crank Angle: here the rotation of the crank or cam shaft via a Magnetic Pickup Unit (MPU) is used to detect torsionals that result due to the the effect of cylinder misfire on engine torque. However, this information is also contained in the ICPS trace.

- Model-Based Techniques: Observer or Model-Based techniques(e.g. Kalman Filters or Neural Networks) aim to reconstruct the pressure trace inside the cylinder by sensing the rotation of the crank or cam shaft plus other signals typically available such as MAF,MAP,MAT and A/F ratio sensors. The advantage is that one can use cheap signals to reconstruct expensive information at the expense of on-board computing resources. On the other hand, Model Based techniques are not discriminatory and in fact work best when combined with at least one excellent sensor, so that they can help or hurt the ICPS emergence.

- Expensive Exhaust After-Treatment Systems: Since ICPS enables lower emission levels at the source of combustion, then the expectation is that cheaper filters with simpler designs will be sufficient to meet the near term emission requirements. Hence the expensive exhaust systems may become displaced or delayed in the near term. However, there is no long term conflict as no matter how low the emission levels are at the source of combustion, the regulations will still push to lower levels.

The above list was not included in the survey so there is no rating information. But Knock Detection and Misfire Detection were highly rated benefits of the the ICPS as reported in section 3.3.3 earlier. The respondents were asked what can disrupt their prediction on the emergence of ICPS. Five people entered the following:

- Reasons:The sensor proved to be unreliable
- Reasons:There is not a whole lot to optimize in combustion with ICPS on a properly operating gas engine, other than spark knock avoidance, Better cyl. balancing and engine noise isn't worth the cost. ICPS doesn't help at all for air or fuel control in gasoline, and isn't that useful for diesel either.
- Reasons:Additional technologies not considered—Lack of understanding of the problem
- Reasons:Potential degradation of drivability and available power
- Reasons:It won't.

System Hurdles on the Path of Engine Developers

What are the biggest Engineering System Hurdles to develop engines that meet the efficiency and emissions requirements?

- *control architectures that are robust with good enough performance and cost (6)*
- *Integration of Different Combustion Modes into One System (5)*
- *Transitioning from a Component Supplier into an Integrated System Supplier (4)*

- Accurate reliability prediction for the whole engine life cycle
- Managing the ripple effects of incremental changes in complex systems
- accurate system validation process
- High fidelity calibration process
- Identifying complex system risks and using them to steer projects and programs
- Managing concurrent development and innovation
- Awareness and Prediction of Impact of Emerging Technologies
- Managing the Trade-Offs between market, business and product architecture
- How to integrate different development time scales between software, mechanical and electronic hardware
- Understanding Environmental Variations
- High Fidelity Calibration Process
- How to apply system techniques to deliver software on time and budget
- Accurate System Validation Process.

3.4 Conclusions on the System Impact and Evolution of the ICPS

The ever increasing pressure on efficiency, emissions, fuel flexibility and the lack of maturity of viable alternatives to the internal combustion engines in the near future, has caused the following clearly identifiable trend:

Trend: Engine Developers are incrementally adding complexity and optimizing components, such as variable geometry turbochargers, exhaust gas recirculation,

> variable valve actuation etc. The unintended consequence is lack of robustness or brittleness that emerges at the system level

This chapter described the technical problem that the combustion process in each cylinder, the source of emissions, efficiency and performance, is very nonlinearly sensitive to the associated variations. ICPS enables closing the loop around the combustion process to improve the trade-off of complexity versus robustness for the engine system as a whole, thereby helping the engine developers maintain bottom line robustness as they add complexity to meet the tighter requirements. But to be part of the solution and not the problem, the ICPS component itself has to have an excellent robust performance at a reasonable cost and size. This chapter tracked the robust design evolution of the ICPS to unravel the architectural approaches of various suppliers to meeting this objective for production engines. The information shows that several suppliers such as Bosch, Beru, Denso, NGK, Siemens and OPTRAND already claim to have solved this problem. The solution is typically in a form that is integrated with another In-Cylinder component such as the Glowplug, Sparkplug, Injector Valve, Cylinder Head etc. Beru already lists the full technical specification of their Piezo-resistive ICPS in their product catalog and may be the sensor that Audi chose for their 2009 Q7 model.

Since the Audi, Cadillac and Honda have not yet released the system architectural details of their designs using the ICPS, this chapter analyzed the literature and interviewed experts to make a detailed list of the architectural impact of the ICPS. The list was then incorporated into an Internet-based survey and sent out to other professionals for rating. Only 21 people completed the survey so it was not possible to perform cluster analysis to extract reliable categories of thought on the system impact of the ICPS. So while the original list is reliable, the ranking that was extracted is not. The following distilled bottom line information on the system impact of the ICPS is therefore "likely to be true" but the real truth will reside somewhere in the much larger space that was detailed in section 3.3:

Key Benefits of Robust Closed Loop Control of Combustion using ICPS:

- Better Cylinder-to-Cylinder Balancing

- Reducing Cycle-to-Cycle Variation in Combustion per Cylinder
- Reducing Emissions

Application Domain:

- Multi-mode combustion Diesel+HCCI and Gasoline+HCCI engines will benefit most. The core competencies required will be *System Integration and Innovative Technology.*

ICPS has Strong Synergy with:

- System Integration: Architectures that are Inherently Insensitive to Adverse Component Interactions
- Ignition Control: Direct or Indirect Control of Start of Combustion
- Fuel Control: Multiple/Tailored Injection Pulses

ICPS has Possible Conflicts with[5]:

- Other Sensors: MAF, MAP, MAT, Air/Fuel, Ion, Knock and Misfire Sensor based on crank angle.
- Expensive Exhaust After-treatment Systems
- Model Based Techniques: Reconstruction of the Pressure Signal from a combination of cheaper sensors by techniques such as Kalman Filters or Neural Nets

Top 3 System Hurdles in Meeting Emissions and Efficiency Requirements:

- Control architectures that are robust with good enough performance and cost.
- Integration of Different Combustion Modes into One System.

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[5] conflicts means that the ICPS can either displace or be displaced by incremental development of one or more conflicting items

- Transitioning from a Component Supplier into an Integrated System Supplier.

Chapter 4

Spillover into the Power Generation Market

> "Strategy without tactics is the slowest route to victory. Tactics without strategy is the noise before defeat.".
>
> –Sun Tzu

It is easy to confirm that spillovers happen between related technologies. Almost any energy system that is used for transportation has a related land based technology with significant probabilities of spillover in either direction. For example Gritsevskyi et. al. [63] modeled the dynamics of spillover between industrial (and residential) and transportation Fuel Cells.

Similarly the new GE LMS100 stationary gas turbine is based on re-using an aero-derivative gas generator core with an industrial low pressure spool that includes the fan and the power turbine. Using gas turbines for electricity generation on land or Marine propulsion is itself a spillover from the aeronautical industry. The land or aircraft versions may look quite dissimilar in some aspects and certainly have different requirements, but the technologies utilized are sufficiently similar that improvements in one can spill over into another. Internal Combustion engines are no exception in this regard. Diesel Common Rail injection first spilled over into the automobile segment from the larger heavy duty trucks and then spilled over again into the large diesel electrical generators. Electronic fuel injection systems is another example application that spilled over from the automotive to the power generation industry. There are many other examples. This chapter first focuses on the issues of adoption of the ICPS technology in the automotive industry followed by analysis of information in the preceding chapters to find the triggers that can cause the spillover of the ICPS into the power generation industry. The reason for focusing on the ICPS technology spillover is that it is as example of a technology that enables *Architectural Innovation*, which is a key capability required for suppliers to move[1] up the system integration hierarchy to capture more value.

Like other markets for mature complex engineering systems, the Power Generation market is slow and so is the pace of associated technology. The typical mode of progress is through planned incremental architectural or component improvements. This is reflected in relatively rigid processes or tacit knowledge embedded in information flow patterns and infrastructure. Meanwhile, the stepwise cyclic implementation of new emission regulations is becoming increasingly harder to comply with, because they kick in at a faster rate than the natural time constant of engine development of typically 5 to 10 years. Given this context, the main focus of this chapter is on how component suppliers may take advantage of this disturbance to move up the food chain to become integrated system solution providers.

This chapter refers to a body of knowledge known as Technology Strategy. The main purpose of this field is not to make better forecasts of future states or strategies that succeed based on the best possible or most favorable future unfolding of events. The purpose is to improve the odds of success no matter how the future unfolds. Raynor's [20] recent book on ”Strategy Paradox” is precisely focused on this issue of how to make the overall strategy robust by employing for example ”real options”.

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[1] This move is a milder form of a more general case, in which architectural innovation enables ”insurgents” to establish a leadership position in the new architecture at the expense of ”incumbents”.

4.1 Adoption of the ICPS Technology in the Automotive Market

Section 1.2.2 pointed to very detailed announcements by Honda, Audi and Cadillac, about their late 2008 and 2009 production engines that will be fitted with ICPS. Chapter 3 referenced a large number of ICPS patents by a number of very credible and established suppliers, OEM's and consulting outfits. Yet, this strong evidence of emergence does not guarantee a successful market penetration. For example, Toyota started experimenting with the ICPS technology 20 years ago and even introduced it into one of their models[44] in 1994. Similarly SAAB started with Ion Sensing about the same time. Both cases did not yield a successful adoption or significant market penetration.

Geoffrey Moore's model of technology adoption explains the phenomena why many technologies or products fail to ”cross the chasm”. His bell curve model in figure 4-1 shows cracks between each phase of adoption and a particularly large chasm between the Early Adopters and Early Majority that he identifies as the most significant hurdle for adoption. The Early adopters are those who expect to ”get a jump on the competition...from lower costs, fast time to market, more complete customer service or some other comparable business advantage...Being the first, they also are prepared to bear with the inevitable bugs and glitches that accompany any innovation just coming to the market”.

The early adopters are specialist technology enthusiasts with product-centric values such as Speed, Ease of Use, Elegant Architecture, Price and Unique functionality. The early majority, on the other side of the chasm are pragmatists with market centric values such as Largest Installed Base, Most Third-Party Supporters, De facto Standard, Cost of Ownership, and Quality of Support. The problem with crossing the chasm is that the technology first develops the product centric attributes that are nothing like or not easily transferable to the market centric attributes needed for convincing the skeptic pragmatists. In the world of integrated system solutions, there is the additional difficulty that the pragmatists are looking for the practical ”system level” market centric benefits that emerges from interaction of cheap and

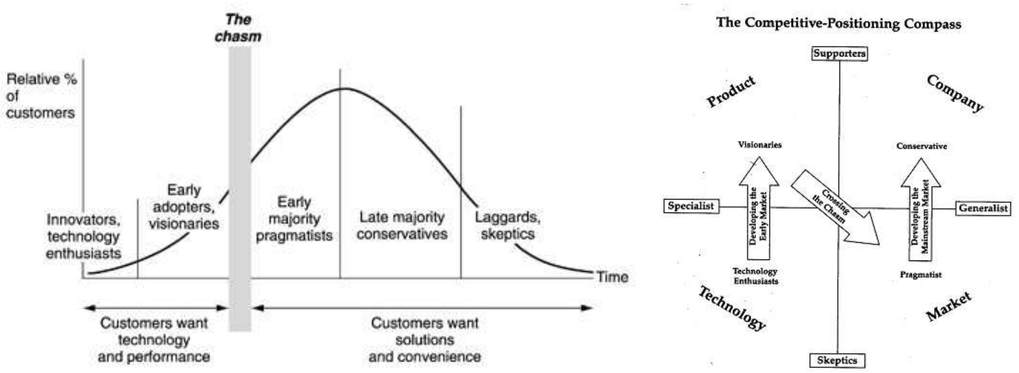

Figure 4-1: Technology Adoption Life Cycle and Competitive Positiotning Compass of Geoffrey Moore [13].

reliable components and cannot easily get excited about ”special” attributes of components.

An element of Moore’s solution to this problem is to define or create a competition, so that by comparison, the new technology looks great. In the world of mature engineering systems however, often one does not have this luxury. A very well defined, and trusted competition typically already exists in the form of a division or unit at the OEM, who is also the customer, would also be typically responsible for delivering integrated system solutions and evaluating competition. For example, the engine OEM’s typically hold on to integrative technologies such as the Controls and Embedded Software divisions. The threshold for accepting alternative solutions from outside the company walls is therefore typically very high.

In Moore’s model the visionary early adopters are willing to live with trading off reliability for some performance or other benefit, chief among which is generating revenue while improving the pragmatic aspects of the system. Only the pragmatists across the chasm care first and foremost about practical issues like reliability. This cannot be further from the truth in mature complex engineering systems that are also safety critical. All parties, including visionaries, absolutely do not have the luxury of a slack in robustness and reliability. For example Audi will never put the ICPS on their 2009 Q7 models to gain an efficiency or emission advantage just at full load at the expense of more frequent misfires or knocks or a cold starting problem etc. A new technology is initially allowed to be problematic in other areas but never allowed to be less robust or less reliable than the preceding products. Boeing aircraft does not have the option of temporarily fatally loosing a larger percentage of passengers in order to generate funds while improving the reliability of their next generation aircraft. Toyota's Prius scored very high on reliability at first introduction. In this domain, everyone is an extreme pragmatist when it comes to robustness and reliability. This is the fundamental difficulty with complex mature safety critical systems: i.e the OEM's take a big risk to pour huge resources to develop a new technology to sufficient maturity, before being able to capture the extra value inherent in the new technology. This is at least one reason why incremental innovation is the main mode of improvement, i.e because the outcome is more predictable. Rebecca Henderson [14] gives other structural reasons discussed later in section 4.4.

To be fair to Moore's model, it is possible for technology to develop in none safety critical applications, i.e. in very different markets. But again the probability of a spillover into the safety critical complex engineering system domain will be low because robustness is an inherent emergent property of the architecture and if a new technology is not robust, it is unlikely that minor tweaking or development will improve the chances of spillover into the safety critical domain. The more complex the system that is supposed to integrate this new technology, the more difficult the spillover. Technologies that have spilled over, such as electronic fuel injection, exhibited cost effective robust performance in their home market before the spillover occurred. So ICPS technology will likely have to demonstrate robust cost effective performance in the automotive industry before it can spill over into the mainstream power generation market.

Now how will the ICPS technology be dynamically adopted in the automotive industry? Struben [2] used a very elaborate system dynamic model to capture the dynamics adoption of Alternative Fuel Vehicles (AFV's) in the automotive industry. Fortunately, the model that he developed has a very generic structure for technology adoption in that industry. The left side of figure 4-2 gives a top level view of his model that includes the dynamics within and between consumer, industry, suppliers (3rd parties) and external factors such as Fuel Costs or environmental factors. The model for example shows how Consumer Choice drives sales that drives R&D that improves the Attractiveness (Price, Performance etc.) that Drives the

Consumer Choice, forming a reinforcing closed loop. Another interesting loop is how Consumer Choice drives Sales that drives Fleet Size that drives Familiarity through networking and word of mouth effects that reinforces Consumer Choice and so on. The special thing about System Dynamics is not that these effects or loops are not known individually elsewhere. But when you have a complex interaction of many loops with nonlinear or high order effects, System Dynamics helps us see the overall outcome and sort out the short term versus long term dynamic effects and helps us determine the conditions where different loops dominate the response. Using this structure, he produced a collection of possible adoption curves as shown in figure 4-2. Note that there appears to be two points of equilibrium. Once the market share rises above some critical value of 20%, there is enough momentum to eventually tend toward a maximum market capture. Below this critical value, all the curves tend toward a low market capture equilibrium or failure. This critical value, is then analogous to the far side of the "chasm" in Moore's model that adoption has to reach, before the dominant dynamics such as sustained price reduction, support and technical maturity ensure a sustained penetration in the market.

By analogy, we can expect that the ICPS technology will either reach the minimum required threshold that will lead to eventual full adoption or it will return to a low adoption level equilibrium that is not sufficient to cause a spillover. In other words, penetration has to reach a relatively high level before one can be certain of a full adoption. A system dynamic model, similar to Struben's[2] but tailored to the problem of ICPS spillover into the Power Generation market can be developed to define early warning signals of full adoption in order to gain some predictive time advantage relative to other players. However this is outside the scope of this thesis.

4.2 Triggers for Spillover

The automotive industry is an excellent source of cost effective reliable technology for spillover, because it is a very large and efficient business ecosystem that generates a lot of value. For example, it is amazing that a mid to high end automobile engine, costs less than a mid to high end bicycle!

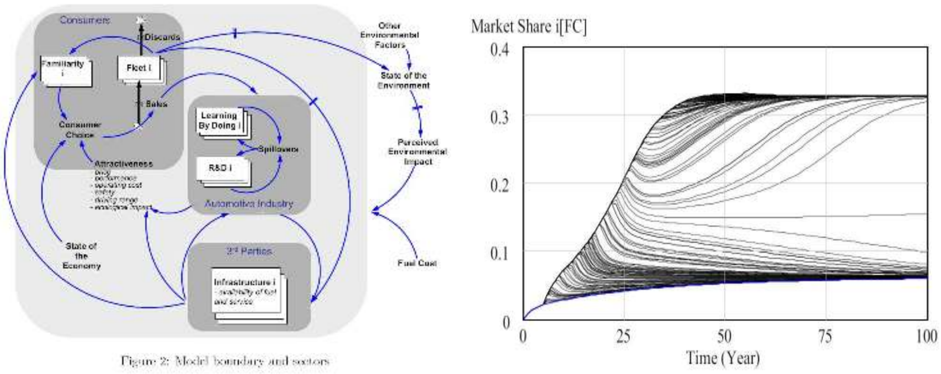

Figure 4-2: System Dynamic Model of Technology Adoption (left) and predicted responses (right) (Copied from Struben [2]).

To illustrate the point, suppose it costs 10 years[2] and 10 people, at a rate of US$ 100,000 to develop a new ICPS sensor and to upgrade the control system to more accurately and robustly control the combustion in a large e.g. 6MW industrial engine used to generate electricity. Let's assume this development cost is to be recovered over the first 5000 engines sold. Then, the price of each unit would have to be increased by at least US$ 2000. However, in the automotive industry, the sales volumes are around two orders of magnitude larger so the same development effort would only increase the cost of each car by around US 20. This is not even a full tank of gasoline!. So, the automotive business ecosystem is an excellent bearer of development costs and reducing unit price while satisfying stringent robustness and reliability requirements. Due to the technical similarity with industrial engines, it is possible that the improvements in the automotive sector will satisfy or surpass some power generation requirements. Hence it is useful to compare some key high level differences of the power generation relative to the automotive industry:

Emphasis on Time-to-Market: is higher in Power Generation. The rate of introduction of new car models every year may give the incorrect appearance that time to market is more critical in the automotive industry. However, the actual rate of introduction of new automotive engine platforms is much slower because a platform is utilized across many model years. In addition,

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[2] 5 years to develop the sensor and 5 years to upgrade the engine, not necessarily in series.

automotive OEM's can afford to employ large parallel development teams and spend relatively larger sums due to high volume and high value nature of the business ecosystem discussed earlier. In the power generation industry, the volumes are orders of magnitude smaller, resources that can be brought to meet a new emission deadline is relatively more limited and the large scale heavy duty infrastructure to design, build and test makes resistance to engine architectural innovations higher. Here only incremental or local "drop in" solutions are relatively easy to deal with.

Emphasis on Conversion Efficiency: is higher in Power Generation . A 1 % average conversion efficiency improvement for a car from say 30 mpg to 30.3 mpg is not very exciting. But the same 1 percent efficiency improvement for a 40% efficiency 6 MW generator that runs continuously for a year is a saving of more than US$140000 per year assuming US$0.03/MJ for price of fuel. Recall from chapter 3 that one benefit of the ICPS was a gain in efficiency, but this was not the main driver in the automotive market.

Emphasis on Misfire and Knock Detection: is higher in Power Generation because a number of factors join to make alternative methods of detection more difficult and less successful here. For example detecting misfires in a 16 cylinder smoother running power generation engine via observing torsionals at the crank shaft are harder than a 6 cylinder automotive engine because missing 1 out of 16 firings in one combustion cycle has less effect on the crankshaft speed than missing 1 out of 6 firings. Being coupled to a stiff electrical grid and higher inertias make misfire detection even more difficult in Power Generation. Partial or intermittent misfires are also harder in larger engines. Knock detection has higher emphasis in power generation because there is a performance versus emissions trade-off advantage by operating closer to the knock boundary in individual cylinders, and engine efficiency has higher emphasis as explained earlier.

Emphasis on Multi-fuel Capability: is higher in Power Generation. This is similar to the emphasis on efficiency argument above. If prices for bulk purchases of fuel (E.g. Natural Gas, Bio-fuels or Diesel) fluctuate and differ even by small margins, then optimizing the purchasing policy of different fuels leads to large fuel cost savings, possibly more than the already significant 1 % efficiency gain explained above.

Emphasis on Robustness and Reliability: is similar in Power Generation. Recall the detailed discussion and definitions of Robustness given in chapter 2 that Robustness is mainly concerned with sensitivity and is a subset of Reliability that also includes a large number of other concerns. The large power generation engines typically have large number of cylinders say 16 versus 6 or 8 cylinder maximum for mass production automotive engines. The more frequent firings per combustion cycle and the higher inertias ensure a relatively smoother combined torque output and smaller torsional modes at the crank shaft. These engines are also relatively more massive and less transient [3] since for example the typical running mode will be at synchronized speed coupled to the electrical grid. Power generation engines are also stationary and not subjected to g-forces. The Cylinder volumes are also much larger and knock frequencies are lower. Combination of all these factors means that the bandwidth and vibration or g-force pickup problem of the indirect sensing ICPS designs explained in chapter 3 are smaller concerns for power generation. Sensitivity to pressure and temperature ranges are similar between the two industries. The main reliability concern with power generation is that the engine must run continuously for very long duration without a malfunction while maintaining acceptable levels of efficiency and emissions. The reliability requirement for ICPS was stated in section 3.1 as the range 0.2 to 5 billion cycles where the power generation requirement is close the the upper bound. So smoother stationary power generation application places less emphasis on robustness but the tougher utilization places more emphasis on reliability so that the components are typically "beefier" or more massive.

Emphasis on Emissions: is similar in Power Generation. The timing of the emission regulations or their cyclic nature may be different between the two markets but the stress that is felt by the OEM's to comply is already at maximum levels. In other words, it is a struggle to keep up with the stepwise emission regulatory push in both industries. Another way to see this is that the regulations push to minimize emissions toward zero in both industries and the targets chosen are always a challenge to meet.

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[3] Full load reject for large power generation engines is a possible exception where the transient requirements are tougher relative to the automotive industry. For example, the injectors may experience too much pressure differential during a full load reject and possibly cause misfires.

Emphasis on Smoothness: Cycle-to-Cycle and Cylinder-to-Cylinder Balancing: is same (i.e. equally high) in power generation. In the automotive industry, smoothness translates to end customer satisfaction. In the Power Generation industry, too much cycle-to-cycle variation limits how closely the engine can run near the knock limit and thereby limits the efficiency. Cylinder-to-Cylinder and Cycle-to-Cycle variations also increase the vibration and noise levels as well as decrease engine life. Section 3.3.2 described how the ICPS can be used to reduce these variations and this ability of the ICPS was ranked the highest in the Internet-based survey reported in section 3.3.3.

Emphasis on Unit Cost of ICPS: is lower in Power Generation because of the fuel cost offset explained above and because the additional unit cost is a much smaller percentage of the total system cost. Note that the price of the automotive ICPS sensor itself was earlier estimated to be around US$10 to US$20 today, and that the automotive industry will probably push it toward the ideal US$5 as the ICPS significantly penetrates the market. Now since the volumes in the Power generation industry are much lower than in the automotive industry, one would expect to pay much more than US$5, but the multiplier is smaller than the effect of system and fuel cost offset. Hence the unit cost improvement of the automotive ICPS that results from large scale adoption is likely to make their cost an easy requirement to satisfy for power generation.

Emphasis on Multi-Mode Combustion: is lower in Power Generation. The main driver for fast transition between HCCI and SI mode (or PCCI and Diesel mode) is the fact that automotive engines are often running at part load. Power Generation engines are mostly operating near full load where they are efficient. However, there is a synergy between Multi-fuel and Muti-mode capability so this emphasis may change in the future for power generation. For example, one reason that the HCCI is limited to part load operation is that it takes time to premix the charge and the available time for mixing is less at higher engine speeds. However, the large power generation engines are running at much lower speeds and there is more spatial opportunity to premix the charge.

The above relative emphasis information was summarized in table 4.1. The table also

Requirement	**Relative Emphasis**	**Trigger for Spillover**
Time to Market	High	High
Efficiency	High	High
Misfire and Knock Detection	High	High
Multi-fuel Capability	High	High
Robustness and Reliability	Same	High
Emissions	Same	Medium
Smoothness	Same	Medium
Unit Cost	Low	High
Multi-mode Combustion	Low	Low

Table 4.1: Emphasis on various Requirements in the Power Generation relative to the Automotive Industry, and the associated probability of Triggering or Catalyzing a Spillover.

includes a column that shows the probability that each item will work as a trigger (or catalyst) for the spillover into the Power Generation industry. This was obtained by further processing the ICPS System Impact information of section 3.3.3. For example the table shows that *Reliability* is similarly emphasized between the two industries and that satisfying this requirement has a high probability of triggering the spillover. The reason is that if adoption crosses the ”chasm” in the automotive sector, there is every reason to believe that reliability will be driven to ideal levels with time. Since this item is similarly emphasized and a key requirement in the Power Generation industry, then there is a high probability that this item can help trigger the spillover.

In other areas, such as Misfire and Knock Detection, the relative emphasis is high but its spillover trigger probability is also high because the technical difficulty of detecting Misfire or Knock from the Cylinder pressure trace is not harder in Power Generation.

The way to interpret the information in table 4.1 is that a number of high probability high emphasis triggers are necessary for spillover and just one trigger may not be sufficient. As mentioned earlier, Electronic Fuel Injection and Common Rail did manage to spillover from the automotive industry into power generation. However, some other technologies have not yet survived the ”scale up” such as Exhaust Gas Recirculation[4] and Piezoelectric Fuel Valves that work well in automotive applications. Nevertheless, once the automotive ecosystem has driven up the reliability, performance and cost-effectiveness, the only hurdles in the path of an ICPS spillover is to develop a rugged (somewhat more expensive) version together with the ability to absorb architectural innovation. The former is relatively routine, but the latter is a typical vulnerability of mature complex engineering system developers as will be discussed later in section 4.4.

4.3 The Status Quo in the Value Chain

A mature engineering system integrator business model typically relies on:

1. Generating Value: that results from the integration of a large number of cheap but reliable high quality components, a significant proportion of which comes from external suppliers.
2. Capturing Value: by supplying high level integrated solutions that solve challenging problems in a way that none[5] can duplicate. Breadth of scope (i.e. the number of components on an engine) is of secondary priority as compared to the differentiation that comes from (almost)unique[6] solutions in the market place.

The total supply chain is made up of connected links where this integrator model recursively holds. In other words, there are multiple tiers of suppliers where the top tier players provide higher levels of integrated system solutions.

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[4] Carter [64] says that ”EGR was studied and rejected by CAT and Cummins for their current off-highway strategy, although cooled EGR remains an option for eventual Tier IV compliance”.

[5] Those who intend to move up the integration hierarchy would need to emphasize uniqueness more than a stable top tier system solution supplier who can coexist or compete with one or two other suppliers.

[6] For example, a control algorithm that improves the coordination of multiple lower quality actuators to improve the system level robust performance, will always trump the solution that replaces all actuators with the same number of more advanced actuators. The former solution is much harder to accomplish and more differentiating in the market than the latter. Even if the advanced actuators are marvelous, they will be perceived as overkill by comparison with the rest that appear to be doing more or less the same thing at a lower price tag.

In this chapter we need to be aware of not applying models that were developed by observing the high tech industry. Some high technology firms such as Microsoft, Sun/IBM, or Nokia tend to dominate the *Platform* around which a large number of third parties prosper. Cusumano [65] describes the evolution of the software business ecosystem into platform leaders and platform complementers. He shows that the success of Microsoft is much more attributable to their platform strategy than luck. Evans et. al. [23] give a range of other examples where Multi-sided platforms have transformed industries such as Google, Apple, TiVO etcetera. Note that the concept of platform in the business sense is quite different to what is commonly referred to as a platform in engineering circles[7].

Unfortunately the domain of safety critical mature complex engineering systems (Aircraft, Automobiles, Power Generation etc.) is very different in nature to the very exciting High Tech industry (Microsoft, Sony, Google, Nokia, Blackberry etc.) that has dazzled most of the scholars that straddle the cross section of technology and business. Here the pace of technology and market is very slow by comparison. The Disruptive Technology framework of Christensen [21] is an example of a very insightful framework but one that can be very dangerous or at least counterproductive to apply in our domain, where the effect of emergence of new technologies is much more subtle. Major technological disruptions are very rare here and advances typically help, not hurt the high level leading system integrators. For example, a very high performance high technology spark plug will just ”drop in” or replace an existing component to benefit several OEM's without disturbing the status quo or putting any OEM out of business! Radical or high technology solutions are either simply not robust enough to work in this tough heavy duty domain, or when robust solutions do appear, it is solely owned or co-owned by the OEM's who continue to maintain their leading position. The gasoline-electric hybrid power plant is an example. It helped the owner Toyota both in profits and the green market buzz, but there are now many other OEM's that benefit by either licensing Toyota technology or developing their

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[7] In a business platform, you have to figure how value (e.g. US$) flows and how a large number of players prosper around an ecosystem and how to ensure a dominant platform leader or complementer role. So leaders or dominant players are concerned about the health and prosperity of the whole ecosystem. In engineering, a platform is a way of solving the major issues once and reusing it cost effectively to generate many derivatives.

own alternative solutions. The next generation alternative Fuel Cell vehicle is also not likely to disrupt major OEM's since the OEM's will be the most likely source of this technology. This however does not mean that emerging technologies have no effect, only that their effects do not resemble disruptive technologies. For example Carter [64] reports that Caterpillar spent US$500 million on its ACERT technology that it expects will make their engines emission compliant for the next 10 to 20 years. So the OEM's are having to spend huge amounts and there is no solid guarantee that the technologies they invest in will definitely deliver robust compliant solutions. Making expensive mistakes is a different effect than not surviving a technology disruption.

Another inapplicable framework is the "Predator/Prey" framework of James Moore [13]. The reality in the heavy mature industry is very different to "cut throat" competition. For example, Airbus and Boeing, two competing lions in Moore's analogy, are happily using a long list of similar top tier system suppliers without getting into battle. There is typically at least two engine choices for Airbus aircraft from a list that includes GE, Pratt & Whitney, Rolls Royce etc. The next generation of nuclear power plants from competing firms GE and Westinghouse will likely use the same supplier from Japan for a critical part. Several automotive OEM's use Bosch fuel system components. Even business acquisitions in the heavy industry are typically "friendly" and not necessarily hostile. So the reality on the ground is more like "coopetition" than competing lions, or Prey that suddenly decide to become Predators etc. It is true that one can gain insights by comparing business to a biological ecosystem. But it becomes dangerous if the model predicts an improbable reality followed by recommendations for executives!.

Note that the "Predator/Prey"[13] and "Disruptive Technology" [21] frameworks are of general applicability and may hold true when considering the total evolution of technologies. For example, Slagle[15] points out that the gas turbine was a radical innovation that disrupted the reciprocating piston engine technology for aeronautical applications and gives data on how its performance and power to weight ratio advantages initially outweigh its immature reliability in the beginning. However, at this mature point in the evolution of complex safety critical power generation systems, the "Predator/Prey" and "Disruptive Technology" frameworks are not particularly relevant, and using them to find solutions for moving up the system integration hierarchy would be inappropriate. So the simple 2 point system integrator business model stated earlier is not bad in the absence of a framework that is actually based on massive observation of system integrators in the heavy industries:

Value Generation. The value generation part works by continuously pushing on the suppliers to standardize their components and improve their quality and price. Competition between suppliers ensures a high degree of compliance. An automotive engine component sale professional told the author that under continuous pressure from their OEM customer, they end up reducing the price of a US$12 component to just US$2 in 5 to 10 years. The suppliers that survive under this pressure are those that can compete on basis of cost or those that continue to add new desirable components to their offering. For the best suppliers in the automotive high volume market, this is not necessarily a bad thing because as a new component penetrate the market, the higher volumes offset the unit price decrease. Unfortunately, this low cost supplier model becomes less sustainable in the low volume power generation market.

Value Capture. The value capture part works by maximizing the cost effective robust performance property that emerges by integrating components. In this heavy duty mature industry, delivering sensitive systems is not an option but a relative robustness advantage for a given required performance is quickly discovered. Charging more than the competition[8] is also not an easy option because the customer usually understands their bottom line well and their cost targets are not very flexible.

The "status quo" is that integrated solution providers tend to keep their position along the supply chain with time and harvest greater portion of the value generated in the supply chain. The component suppliers on the other hand tend to feel squeezed with time because it is difficult to keep cutting costs or maintain a regular predictable innovative output in the form of new components when not capturing much of the value generated in the supply chain. Moving up the ladder for a component supplier would normally mean that the high level integrator who is also the customer, would be willing to give up a piece of its high value capture activity.

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[8] in some Financial/Banking circles, a lower price may have a negative perception about system quality.

For suppliers deeper in the supply chain, it is usually true that moving up the chain by delivering higher integration levels will be more profitable and sustainable[9]. But at higher integration levels, this is not always clear. For example, will Caterpillar capture more value if they move up the chain to become an electric production utility? or will GE Aircraft Engines capture more value if they had the capability to manufacture aircraft? Carter [64] mentions that Cummins has already decided to move up a level:

> ”In fact, Cummins prefers to be known as more than just an engine builder: ”We want to be the company that can supply not just the engine, but everything around the diesel as well,” says Mark Levett, vice president and general manager of Cummins HHP, referring to Cummins subsidiaries such as Holsett (turbochargers), Fieetguard (filtration), and others. ”Robust engine design and a strong distribution system are required for success in high load factor, high service hour applications such as mining, but customers want their engine builders to provide the total package.””

Unfortunately, there are many hurdles in the path of moving up the system integration ladder. A side effect of the mature slow industry is that component oriented culture, processes and infrastructure are deeply ingrained in their organization. For example, they may suffer from the tendency of solving the system integration problem by doing what they do best: designing better or more sophisticated components and not attempting to maximize the robust emergent properties at the higher integration level. Nevertheless there are examples of companies that managed to get promoted to the next level and companies that were demoted to the lower level and the key question is how they did it.

The author found no reliable in depth scholarly focus on the topic of moving up the system integration value chain in any of the complex engineering system industries such as aerospace or power generation. Yet there are a few technology strategy publications that help answer

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[9] This holds true for systems where integration is difficult, such as power generation systems. In a different PC world today, many OEM’s are adding little value at the system level, because integration is relatively easy, and the value flows to vendors of common components (such as Intel or Microsoft).

some basic questions in the absence of hard evidence. These are utilized in the next section to give some strategic recommendations for moving up, in the context of combustion control systems and the emergence of ICPS.

The main take away from this section is that the position of top system integrators in the mature complex engineering system industry is inherently stable and not easily influenced by the emergence of new technologies, or the cyclic implementation of new emission regulations. Furthermore, moving up the the system integration ladder in this domain presents special challenges that have not yet been studied by scholars in depth.

4.4 Strategic Recommendations for Moving up the System Integration Ladder

Technology Strategy is a way of structurally improving the odds of success by extracting useful high level information or patterns by integrating existing or past information. The useful references are not about formulating a special forecast or a plan that only works when this forecast becomes true. For example, our strategy should not be based on the assumption that housing or oil prices will continue to rise, although this may appear to be very likely when we are formulating the strategy. It should also work when these prices fall, oscillate or remain steady. So just like complex engineering systems, the business strategy has to be robust, and robustness is first and foremost determined architecturally. Again, tweaking the parameters of a fixed architecture has only secondary effect. We can increase the percentage of R&D funds or allocate more resources to move up the system integration ladder, but if that is all we do, the gains will quickly reach the inherent limit that is set by the organizational architecture. If a company's revenue has a long history of primarily coming from supplying components to mature industries like aerospace, automotive, or power generation, then there is no reason to believe that its existing organizational architecture or its successful people are already perfectly aligned for moving up the integrated system value chain to capture more value.

Unfortunately, the majority of reputable technology strategy references is focused on the faster dynamic effects of the high tech industry or trying to formulate a unified theory to solve the problem for everybody. One reference captures part of the problem with mature complex engineering system suppliers, where the business dynamics are slow. Rebecca Henderson [14] describes the context of the problem as follows:

> ”...no one individual can be an expert in multiple technologies, markets, and processes required to design an object of of any sophistication...Architectural knowledge is both knowledge about the linkages between components, and knowledge about the impact design decisions made in one component are likely to have on another... After an initial phase of rapid exploration and diversity, most technologies evolve towards a ”dominant design”... Once a dominant design is in place, the development of new component knowledge becomes a constant focus...Since in this regime, the relationship among components do not change, architectural knowledge tends to become embedded in the tacit knowledge of the organization, a part of the organizational furniture... As long as the technological and commercial environment of a design group remain stable, the embeddedness of architectural knowledge can be an enormous source of strength.

This is a key insight. For example, by stealing the top engineers or managers away from a mature system integrator OEM, a component supplier will not necessarily move any closer toward becoming a system integrator for that OEM or any other. The key about ”tacit” knowledge or the essence of what makes an OEM great at what they do is not explicitly captured in some database or known by a few people. Henderson explains that this essence is implicitly deeply ingrained through incremental evolution in the communication, organizational, process, accounting, reward systems and other ”organizational furniture”. An Intel manager recently told the author that their distributed design centers around the world are almost ”exact copies” (equipment, processes, reporting structure etc.) with a clear intent to minimize the differences between them. Other than the obvious resource flexibility, part of the reason is that they have something that works that is not explicitly captured in a few basic rules. It is all or nothing. There is a famous engineering story about an aircraft engine component called a curvic coupling, that the organization was afraid to modify thirty years after it was designed because the people who understood it were retired or gone. Mechanical engineers today, have tools that far surpass what was available thirty years ago to improve or replace a mechanical component. What was missing was that they had no idea how a change here would ripple across the rest of the complex system. By not touching it and working around this component, they could minimize the uncertainty.

Henderson[14] correctly points out that as long as there is stability, ”tacit knowledge” is a competitive advantage and source of strength. However, this strength is also the cause of vulnerability to ”Architectural Innovation”. Figure 4-3 shows her framework for categorizing innovation. The modus operandi of mature engineering system developers is in the upper left quadrant tagged *Incremental Innovation* where the Core Concepts are reinforced and linkages between Core Concepts and Components are unchanged. An extreme form of incremental innovation is a ”drop in” replacement of a component with a more advanced component that has very little ripple effect on the rest of the system. Architectural innovation is in the lower left quadrant of the figure. This mode reinforces the core concepts but the linkage is changed. For example, the emergence of ICPS technology does not change the core concept that the emission and efficiency performance engine must be robust. This has been the core concept for a very long time. However, using the ICPS shifts the strong reliance on open loop characterization and external integral sensors toward feedback control with an individual sensor in each cylinder that directly measures combustion.

Slagle [15] correctly points out that gas turbines represent a radical innovation compared to reciprocating engines for aircraft application. But now, after about 80 years of sustained development and large scale adoption, the typical innovation mode is incremental. Today, the proportion of characters like Frank Whittle or Hans von Ohain who understood most of the system issues of their concepts at the time is small, in favor of a large portion of mature engineers who deeply understand a small piece of a much complexer system working in an organization that ”tacitly” ensures robustness. Again, the faster rate of appearance of new engine models can be deceiving. In fact, an engine platform is designed once and many derivatives are generated

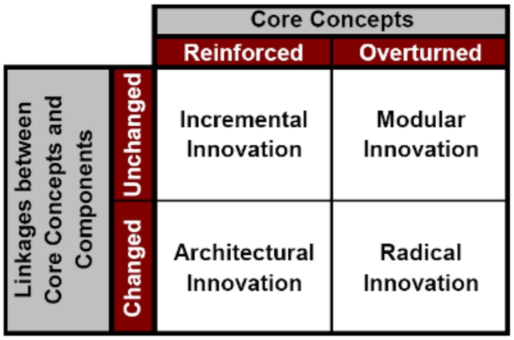

Figure 4-3: Rebecca Henderson's[14] Framework for architectural categories of innovation.

from it, reusing as much of the common core as possible.

Incremental innovation has a self perpetuating effect causing stability. For example, during 80 years of gas turbine development, the older technical system level experts and their associate "tacit" knowledge have been disappearing through retirement or other secondary effects. On two large system level jobs that cannot be detailed here, some key design decisions made by the engineering team at two different OEM's was primarily based on the author's ability to simulate the dynamic response and robustness analysis of the integrated fuel system, where the focus was on adverse effects that arise by the interaction of components. This level of reliance on external expertise was rarer before the knowledge drain started. The interesting issue was that the system was made of a number of third party components, whose suppliers had zero knowledge about the dynamic response of their component, let alone how this would interact with the rest of the system. So long term sustained incremental innovation is burning the stick as both ends: The OEM's are slowly loosing their tacit system integration knowledge[10], and many component suppliers do not have a reason to hold on to or develop enough expertise beyond low cost manufacture of their components to a fixed spec. This is an opportunity for players who want to mean more to the OEM's that they do today.

Another factor is that the most prized emergent property of mature safety critical systems

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[10] A key component of tacit knowledge are the people and their interactions, so just hiring new people by itself cannot fix the drain, because there is no explicit database for the new people to learn from.

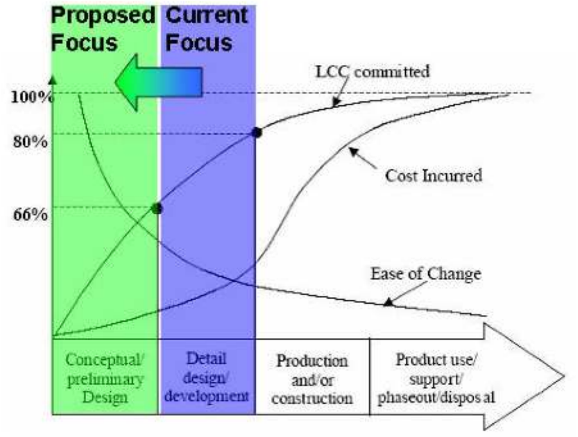

Figure 4-4: OEM's are under investing in Conceptual and Preliminary Design. Slagle proposes a architectural approach for improving the robustness of complex systems upfront. (Figure copied from Slagle's thesis [15]).

is robust performance, a property that is above all determined by the system architecture as explained earlier in chapter 2. Instead the OEM's are spending the majority of their resources in the detailed design of complexer or more advanced components, and compliance phases that only yield small gains. Jason Slagle [15] identifies this gap and recommends focusing on the conceptual and preliminary design phases, shown in Figure 4-4, where the robustness return on investment is high. The figure shows that the majority of the the OEM effort is spent in areas that determines 34% of the life cycle cost where ease of change is relatively low, versus the upfront phases that determines 66% of life cycle cost, where the ease of change is relatively high. There are examples in the literature, such as Shahroudi [66] who proposed a modern approach for multi-disciplinary conceptual/preliminary design process for gas-turbine based aircraft engines. Hence the problem is not about lack of approaches, the problem is with the incremental innovation "lock in" that dominates.

The opportunity provided by the OEM's lack of focus on up front design phases raises an interesting question: Can consulting firms (such as IAV or FEV) or others who presumably have a lot of integrative and in-depth specialist knowledge, break away from the OEM's and independently deliver superior engines to capture a slice of the market? The answer is probably no, because :

- none OEM's do not have anything that replaces the OEM "tacit" knowledge that is responsible for achieving the required robust performance levels for safety critical systems.
- the resources required for R&D,compliance and testing, dwarf any capacity that none OEM's can muster. Carter [64] mentioned a budget of US$500 million and US$200 million for the Caterpillar ACERT program and Cummins R&D respectively. This order of magnitude ensures a significant barrier to entry.
- OEM's own the "data". Making a solution in a lab under controlled conditions is a million miles away from a robust system that in the field can be relied on. No amount of self congratulation or hype will help if the system is not robust to "real effects" in the field. Only the OEM's own the data that captures these unwanted real effects. This data was paid for heavily through decades of testing that only radical innovation can render inapplicable. Slagle [15] tracked the robust design evolution of the jet engine. In 80 years of development, the main mode of innovation was incremental or rarely architectural, never radical.

It is very interesting that suppliers typically try to interface very well with the commercial or operational units at the OEM because after all, these are the people who actually sign the checks. This is in line with the normal intuition of sales to sell to the economic buyer and not the enthusiast. Direct communication between the technical experts of suppliers with the OEM's, is relatively rare or happens indirectly via the commercial people at the two ends. This model probably works very well in majority of cases where we are not dealing with mature complex engineering systems that are also safety critical. Here again, the key card that trumps everything else is robust performance. So the suppliers can strike an extremely close commercial relationship with the OEM's, yet despite all the good will and pressure from their commercial colleagues, if the engineering organization feels or can show that the supplier proposed solutions are not robust or not a significant improvement, the deal will eventually break. So the direct commercial relationship should be balanced with direct technical relationship, particularly with the upfront conceptual/preliminary design people at the OEM or their customers. These groups are typically not the center of attention as they are not absorbing large funds, but are the people actually charged with improving the architecture of their systems to gain robust performance. A direct technical relationship with them would in the very least, inform of the hot architectural issues and possibly some early warning on the form of integrated system solutions that are likely to be pursued soon or in the near future.

Ultimately strategic recommendations for those who want to move up the system integration hierarchy is twofold: *Value Generation* and *Value Capture*. Recommendations are also very supplier and situation dependent because for example, some component suppliers may have had a higher level system integrator role in the past, who may have an easier path than others who have always been component suppliers. As mentioned earlier, there is a lack of directly applicable technology strategy references focused primarily on mature complex safety critical engineering systems. The following recommendations is based on the authors own experience and analysis of information in the literature referred to in this thesis. Here are my generic recommendations for value creation for a hypothetical component supplier:

Value Creation:

1. *Focus on Architectural Innovation*: This is an area where the OEM's are vulnerable and one of the few areas for high level work in system integration where the OEM's need and would presumably appreciate help.

2. *Establish Technical Contact*: with the technical professionals responsible for conceptual/preliminary design at the OEM's and their customers.

3. *Generate Integrated System Models*: As a matter of principle, generate state of the art control oriented system models for all the different systems that are now being supplied with components. The OEM's have relied on their "tacit" knowledge that is draining through aging workforce and retirement. Other pure component suppliers have increasingly less idea on how their component behave dynamically. Hence system models that capture explicit knowledge become increasingly valuable with time.

4. *Generate Engineering Real Options*: Generated high level integrated system solutions on paper, up to and including a working prototype, but not all the investment that goes into making an actual product. A common mistake is to only work on component projects requested by the commercial side of OEM or people working at or near the tail in figure 4-4. Moving up the integration hierarchy requires a fast exercise (i.e. Fast Time to Market) of this type of option.

5. *Invest in Integrative Technologies*: The gap between some of the integrative technologies applied in the OEM's systems and available technology continues to increase because they can typically only absorb incremental innovation. For example, the control algorithms used to control commercial gas turbines today are typically at least 30 to 40 years behind the more recent robust controls or distributed controls theory. Software as an engineering system is another area because the cost of software development and V&V is becoming a very significant development cost. The phobia of losing robustness or the possible ripple effects are the reason why the OEM's are not taking the risk. This is another opportunity for value creation.

6. *Invest in People and Skills*: Chapter 2 gives a detailed approach for identifying the generic and specialized skills based on the system type hurdles or symptoms. This can be based on the OEM's hurdles to see what skills to invest in to better complement the capability at OEM's.

It is much harder to give value capture recommendations because so much depends on the specifics of the players and the situation. Disruption in mature industries is almost nonexistent and the leading OEM's are very stable. Still market capture shifts between the OEM's is possible. In addition, opportunities can and do arise for value capture for suppliers. Here are some example opportunities for value capture:

1. *Technology Spillover*: such as the ICPS technology from the automotive into the power generation industry. It will take a relatively long time for the established OEM's to incorporate a spillover that requires architectural innovation. In addition, other OEM's

who have not invested heavily or "locked in" to a particular technology, can make a significant leap by adopting a ready to go total integrated solution.

2. *Ignored Installed Base*: As new emission and efficiency regulations kick in, a huge number of engines in the installed base will immediately not qualify. In some cases, the OEM's may ignore the installed base because their efforts are focused on the latest greatest engine platform. Under these circumstances, the OEM may be happy to outsource the full integrated system solution to third parties who would not be competing with internal business units but helping them with what they perceive as less profitable and more difficult work.

3. *OEM Miscalculation*: OEM's are not infallible and do sometimes gamble on the wrong technologies so that their new platform may not qualify the looming emission levels. This kind of mistake is rare as the regulation cycles are known many years in advance and as incremental technologies have a smaller risk. But the probability for a mainly component supplier moving up to tier 1 integrated system solution provider is also rare. So the supplier must take advantage of rare events by having "real" options that can be exercised quickly (i.e. fast time to market) once a rare opportunity arises, before reverting eventually back to the status quo.

4. *Advantages of Being Small*: Suppliers, having survived continuous pressure to cut costs, tend to have faster approaches with relatively lighter baggage. If they can avoid falling into the trap of emulating the OEM, by for example blindly copying their elaborate processes, and instead focus on architectural innovation, they stand a good chance of becoming a top tier system integrator partner because they can help reduce the OEM's heavy cost of compliance with regulations, if not the overall size of the pie.

4.5 Conclusions on Technology Strategy

Becoming a top tier system integrator in the prime mover business is a very noble objective, particularly since the OEM's are gradually loosing their tacit knowledge or organizational "furniture" as people retire and as other component suppliers are getting further pushed into the corner of competing on price. But the path to this objective is full of caveats. Some of them are due to the status quo and the extreme stability that rules in the mature safety critical world where "Predator/Prey" or "Disruptive Technology" models do not apply. But others are facets of resident component supplier culture that dominates because the majority of revenue is coming from component sales.

For example, a knee jerk component oriented reaction to the emergence of the ICPS in the automotive industry might be to acquire or bring in-house the capability to develop and manufacture the ICPS component, in the hope of gaining at least a short term system integrator advantage by being the only supplier with the ICPS in the power generation market. But this relies on the best possible outcome of this move. One problem is that the ICPS component may in fact not get massively adopted in the automotive industry despite an impressive early emergence or adoption, as simulated by Struben's System Dynamic model in figure 4-2 or by Moore's crossing the "chasm" in figure 4-1. Not getting properly adopted in its home market also reduces the probability that it will ever spill over into the power generation market. But the other and possibly more significant issue is that the ICPS will not benefit from the cost effective robust performance that successful adoption in the automotive industry would automatically bring as explained in detail previously. Yet another caveat is that in both the automotive and power generation, there typically emerges at least two or three dominant suppliers of components so the advantage gained will be very short term. Some of these players like Bosch operate in both markets and have some integrated system level capability. This type of supplier is better positioned to engineer a spillover if the market turned out to be interesting for them. A better strategy might be to focus on generating and capturing value at a higher integrated system level that does not care who supplies the ICPS component. Rebecca Henderson's [14] and Jason Slagle's[15] insights are very valuable here because they point to a particular high value generation and capture domain, namely architectural innovation, in the conceptual and preliminary design area with the target of delivering on robust performance that is a higher level emergent property of interaction of components.

Another recommendation is to invest in the essential System Engineering skills and processes that is missing in the supplier organization. This one is also not simple because one cannot emulate the OEM's for a couple of reasons. First, the OEM's success is based on "tacit" knowledge and may not be repeatable elsewhere unless huge resources are expended to make almost exact copies. This can kill the advantage of being small and lean. Second, the OEM's do not need much help or competition on what they do best, namely "incremental innovation". So the skills and processes that are likely to create value and capture opportunities may be related to but are not necessarily very similar to those of the OEM. Therefore blind copying of the top notch integrated system solution suppliers is not directly fruitful. It would be helpful to find out how a component supplier managed to cross over and what path they followed in the targeted industry. However, if this was a recent move, why would they divulge the secret? If this move happened a long time ago, they would not know explicitly what caused their success, since the real factors are embedded in "tacit" knowledge.

A better way to identify the required skills would be to detect the hurdles or existing symptoms that are in the path of becoming a higher level integrator and use a framework like that given in chapter 2 to discover the highest ranked general and specialized system design and management skills that overcome these hurdles. This is more likely to succeed because the skills are tailored to solving actual problems at hand versus blind copying of OEM's or strong opinions that solve an unknown or a different problem. This framework was based on detailed response of 690 professionals with an average of 20 years work experience spread across business, management and engineering functions.

Section 4.4 analyzes the System Integrator's business model and gives a number of generic strategic value generation and value capture recommendations that will improve the odds of success of suppliers intending to move up the integrated system hierarchy.

4.6 The Bottom Line Conclusion

This thesis has covered a very wide range of socio-technical issues, from the emergence of the ICPS technology in Chapter 1 to robust design compass in Chapter 2, to architectural evolution of the ICPS sensor and its system impact in Chapter 3, to technology adoption, spillover triggers and strategic recommendations on how to move up the integrated system solution hierarchy in Chapter 4. The big hurdles in real systems do not live in pure disciplinary domains or individual divisions inside an organization. They live in a very different world that emerges from the interaction between these elements inside and across organizations. This may be counterintuitive for engineers who for example see one of the most complex and reliable creation of man, the gas turbine, as a purely technical system, or commercial professionals of suppliers who are mainly following the money not realizing that the key to their success may come from establishing technical contact or planting seeds with the lower profile groups at the OEM's who are busy in the upfront conceptual or preliminary design phase of their next generation platforms. Hence one needs to focus on a range of issues in the socio-technical spectrum to find some answers when dealing with complex systems.

Each of the chapters in this thesis has its list of conclusions, and may be perceived as hitting on "too many notes" so to speak. But here is a couple of bottom line high level conclusions that this thesis as a whole supports:

- *The key to ensuring success in mature prime mover industries is the explicit understanding of how to generate and capture the cost effective robust performance value that emerges from the interaction of simpler socio-technical elements.*
- *An opportunity to learn from failures, or a good way to avoid them, is to gain structural understanding of the dynamic causal loop relationship between the above value and the value measured in dollars.*

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