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▶ To cite this version:

Aydin Nassehi, Richard Allen, Stephen Newman. 18th ICPR paper: Application of mobile agents in interoperable STEP-NC compliant manufacturing (submitted for best PhD paper prize). International Journal of Production Research, Taylor & Francis, 2006, 44 (18-19), pp.4159-4174. 10.1080/00207540600786723 . hal-00512919

HAL Id: hal-00512919

https://hal.archives-ouvertes.fr/hal-00512919

Submitted on 1 Sep 2010

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Journal:	*International Journal of Production Research*
Manuscript ID:	TPRS-2005-IJPR-0579.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	14-Apr-2006
Complete List of Authors:	Nassehi, Aydin; University of Bath, Mechanical Engineering Allen, Richard; Loughborough University, Wolfson School of Mechanical and Manufacturing Engineering Newman, Stephen; University of Bath, Mechanical Engineering
Keywords:	STEP NC, CAM, CNC
Keywords (user):	Mobile Agent Systems, Interoperability

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Application of mobile agents in interoperable STEP-NC compliant manufacturing

A. Nassehi[*]†, R. D. Allen‡ and S.T. Newman†

† Department of Mechanical Engineering

University of Bath, Bath, BA2 7AY, UK

‡ Wolfson School of Mechanical and Manufacturing Technology

Loughborough University, Loughborough, LE11 3TU, UK

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As the ratio of transport costs to total product cost increases, manufacturers try to fulfil the demands of each geographical region with products manufactured within the same region. Since the manufacturing resources available at each venue can be varied, it is necessary to adapt the manufacturing process plan for each production facility. Traditionally this process is carried out manually by engineers utilising CAD files. With the advances in artificial intelligence technology and emergence of integration standards such as STEP, it is now possible to automate the CAD/CAM/CNC

[*] Corresponding author. Email: A.Nassehi@bath.ac.uk Telephone:+44 (0) 1225 384801

interface. Distributed artificial intelligence techniques and mobile agents in particular can be used to transfer information throughout the manufacturing network and construct the distributed knowledge-base required for the intelligent interoperable integration of product data models and manufacturing resources. This paper explores the application of mobile agents as enablers of interoperability in a global manufacturing enterprise. A novel manufacturing chain based on the STEP-NC standard is proposed and the application of agents for transfer of manufacturing information is studied. The research is demonstrated through the use of a prototype manufacturing decision support system developed using agents.

Keywords: CNC; CAM; Mobile agent systems; STEP-NC; Interoperability; AI in Manufacturing Systems

1. Introduction

In the recent years manufacturers have been facing an increasing amount of competition from countries with low wage economies (Hine and Wright 1998). This has triggered a shift towards a restructuring of resources to rely on automated manufacturing techniques such as CNC more than ever. The manufacturing cost of products has therefore decreased. As a result the transportation cost has become a major contributor to the final price of goods. A few years ago, it would have been feasible to manufacture a particular product at a central facility and ship it worldwide. But now in order to maintain profitability, companies have been relocating their production facilities closer to their markets. It is not

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uncommon for a company nowadays, to have several CNC manufacturing venues around the world to address the demand of each region with the products manufactured in a local plant (Pontrandolfo and Okogbaa 1999).

One of the hurdles for the realisation of this idea is the fact that the facilities available in each manufacturing venue may have been configured differently. Having diverse CNC machining resources often means having to cope with numerous versions of programming specifications. This in turn translates into the need for additional post processors and expert manual input.

Currently, if a manufacturing firm wishes to make the same component on various machine configurations, the CAD files are sent across the world to the company's subsidiaries. There the files are interpreted by engineers present at each venue and local process plans suitable for each individual centre is generated according to the machine configuration available.

While this solution might be practical in some cases, there are many situations where there is a need to transfer some specific manufacturing instructions together with the geometry information of the part. This is not possible with CAD models. Furthermore individual interpretation of CAD models in different venues can result in different process plans for a single component. This de-standardisation of manufacturing processes is usually undesirable.

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A better solution for global manufacturing would be to have an interoperable process plan (See section 2) for each product that can be interpreted according to capabilities of the machining facilities available at each venue. This process plan should be capable of transferring the component design together with any specific manufacturing requirements and pre-defined processes to all satellite venues.

The STEP standard (ISO10303-1 1994) has started to emerge as the integration platform for engineering and manufacturing data transfer. STEP-NC (ISO14649 2002) specifically address the information requirements of CNC manufacturing by providing a hierarchical data structure capable of storing manufacturing processes in an interoperable manner. STEP-NC can therefore be utilised to create a framework for the transfer of required information worldwide in a global manufacturing scenario.

Generating the interoperable process plans and interpreting them into manufacturing resource specific instructions requires considerable intelligence. As planning and manufacturing in a global firm is carried out on a distributed network of computers, distributed artificial intelligence is an excellent candidate for the implementation of the required intelligence.

This paper examines the application of intelligent agents and mobile agent systems as a practical representation of distributed artificial intelligence for the implementation of interoperability in the STEP-NC manufacturing chain. A brief overview of interoperable STEP-NC process planning is followed by an introduction to agent systems. The

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information contained within the STEP-NC manufacturing chain is then explored and the application of a mobile agent system for implementing interoperability throughout the chain is discussed. A prototype mobile agent system is finally utilised to demonstrate the applicability of the mobile agent technology in achieving interoperability.

2. Interoperability in a STEP-NC compliant manufacturing chain

Interoperability is the ability to transfer semantics from one computer system to another with minimal manual intervention (Hasselbring 2000). In the context of this research, the term interoperable is used when a manufacturing process plan can be executed by various manufacturing resources with minimal human involvement. To assess the advantages of implementing interoperability in the CNC manufacturing chain it is necessary to identify the domain within which the CAx chain takes form.

2.1 STEP-NC compliant manufacturing

Computer numerically controlled (CNC) machines are normally programmed in accordance to the ISO 6983 standard informally known as G&M codes. These programs contain axis movement and simple switching instructions (ISO6983-1 1982). These instructions are machine and set-up specific and if a certain part has to be manufactured on two different machines with different configurations, two sets of instructions would be required. The need for machine specific instructions seriously undermines interoperability in the process plans generated according to ISO6983 standard (Xu 2004). The traditional CAx chain for CNC manufacturing is depicted in Figure 1.

[Insert Figure 1 about here]

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In this chain the component is first designed using CAD tools. A process plan is then generated based on the geometry information contained in the CAD file. Feeds, speeds, strategies and technologies are chosen by the user and the toolpaths are generated based on these choices by the CAM software. An NC file is then generated a by a post processor specific to a machine. This file contains low-level NC functions and tool axis movements.

ISO 14649(ISO14649-1 2002) and ISO10303-AP238 (ISO10303-1 2004) provide an alternative approach to programming CNC machines. Instead of specifying how a part should be manufactured i.e. by specifying axis movements, these standards contain information about what needs to be manufactured (Newman 2004). These standards commonly known as STEP-NC rely on features to specify manufacturing processes. While it is still possible to define cutter movements as part of the STEP-NC information for a component, this definition is optional and is not needed for the manufacture of the component (Xu et al. 2005).

As resource dependant instructions such as tool changes and tool axis movements are not required in a STEP-NC programme, it is possible to specify what needs to be machined in a resource independent manner. A STEP-NC process plan can therefore be interpreted prior to program execution to adapt to the machine configuration that will be used to manufacture the component.

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2.2 STEP-NC manufacturing chain

In a global manufacturing enterprise with a number of subsidiaries around the world the CAx chain will expand to include the different machining facilities available at each satellite location. Figure 2 shows a possible configuration of STEP-NC CAx chain for a global manufacturing company.

[Insert Figure 2 about here]

The component is designed in the company's head office and the interoperable process plan is generated based on this design. The interoperable process plan is then transferred to each subsidiary where it is interpreted according to the machining capabilities that exist within that subsidiary.

The interpretation is handled by a machine specific STEP-NC interpreter that automatically generates NC files suitable for the active machine configuration. This manufacturing resource specific manufacturing file can have many formats ranging from a proprietary feature based manufacturing language i.e. Siemens SHOPMill's MPF files (Siemens 2005) to ISO 6983 compliant G&M codes with machine specific additions. The STEP-NC interpreter needs to be developed by the CNC controller vendor.

In cases where the level of the resource specific protocol is high enough to allow feature based programming with semantics similar to those of STEP-NC, it would be possible to have bi-directional information exchange. This would allow the shop floor changes to be reflected back along the CAx chain to update offline product and process models.

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3. Intelligent agent systems

Intelligent agents are the practical implementation of distributed artificial intelligence methodology. Each individual intelligent agent is an intelligent entity that is autonomous to a certain degree, has sensors to sense its surrounding environment, has a goal or agenda to pursue and has effectors to make changes in the environment (Woolridge 2002). Agents have been categorised according to their functionality by researchers. Nwana (1996) provided an extensive typology of intelligent agents that can be seen in Table 1.

[Insert Table 1 about here]

While individual agents are extremely effective at performing tasks like gathering information, the real potential of agent systems is realised when they are combined in Multi-Agent Systems. Usually different types of agents are combined in the Multi-Agent Systems to achieve better functionality. An interface agent might collect the data from the user and pass it on to a number of information agents. The information obtained from these agents can then be passed on to a system of collaborative agents to choose the best solution among a number of solutions. The result is passed back to the interface to be shown to the user. Allen et al. (2004) showed how a multi-agent system can be utilised to perform computer aided process planning within a STEP-NC framework.

These systems are very effective in solving complex problems where the solution can emerge from solving a great number of smaller problems linked together. Individual agents

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try to solve the small components of the problem while maintaining the feasibility and integrity of the solution through communication with their peers (Woolridge 2002).

Taking the multi-agent concept one step further are the mobile agent systems. In these systems the intelligent agents reside on different computers connected through a network or the Internet and are able to move from one system to the other when instructed to do so. The mobile agents can preserve their state through the utilisation of persistent contexts. In other words, the mobile agents retain the values of all their variables when transferred and can therefore continue execution when moved from one computer system to another (Picco 2001).

While it is possible to develop agent systems using general programming languages that provide multi-threading capabilities (Bigus and Bigus 1998), the development process is cumbersome, complex and repetitive for the majority of the code written.

To simplify development of agent systems a number of agent development platforms have been created. These platforms handle the creation, execution and disposal of agents as well as brokering the messages sent by the agents automatically.

A well known platform for developing mobile agents is the Aglets (Oshima 2005) platform originally developed by IBM (Lange and Oshima 1999) and recently released as open source software on the sourceforge (Sourceforge 2005) software repository.

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Software agents created using the Aglets platform have the inherent capability to send and receive messages and hence it is possible to develop multi-agent systems based on aglets with relative ease. Being based on java, aglets are portable to various computer platforms and can be utilised in different computing environments.

The Aglets also have the ability to migrate from one computer on the network to another running the aglet server platform. The migration capability makes the aglet platform suitable for developing mobile agent systems.

Mobile agent technology has been utilised in CAx manufacturing research by a number of researchers. Zhou et al. (2002) developed a model for a distributed internet-based scheduling system for the manufacturing chains based on Aglets. In thier model, scheduling is handled in two levels. In the high-level scheduling, Aglets support the operation of manufacturing venues and cells. In the low-level scheduling, working procedures over manufacturing equipments are decided by Aglets. Zhou and Jiang (2005) later used the mobile agents to encapsulate manufacturing resources to allow them to communicate over the internet. This approach allowed legacy CAD/CAM and CNC software to communicate via an Internet Protocol (IP) network. A number of advantages were identified in employing mobile-agents when compared to other software message-passing systems.

Krishnamurthy and Zeid (2004) employed Aglets to provide information services to the workforce in motion within manufacturing enterprises. XML was utilised for inter-agent communications. Moonsoo and Mooyoung (2004) developed a mechanism called mobile

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agent-based negotiation process (MANPro) to support the creation of a distributed shop floor control system. In this mechanism the control is achieved through negotiations between autonomous agents.

Considering the support Aglets have received as the platform of choice for development of mobile agents in manufacturing together with the convenience of utilising a ready-made template for developing messaging and mobility functions, the implementation of an interoperable system using mobile agents has been tested on the Aglets platform.

4. Mobile agents as enablers of interoperability

Mobile agents can be utilised to create an integrated STEP-NC compliant manufacturing chain. To identify the challenges involved in creating such a chain that is also capable of supporting interoperable manufacturing, it is necessary to recognize the semantics involved in CNC manufacturing and mapping the capabilities provided by STEP-NC onto these information requirements.

4.1 Layers of manufacturing information in STEP-NC

The information in the STEP-NC structure is divided into three sections: workplan and workingsteps, geometry description and finally the technology description. Figure 3 illustrates how these sections extend as layers across the manufacturing chain. When organised in these layers the information contained within the STEP-NC organisation can be linked directly to the process that generates the information.

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[Insert Figure 3 about here]

Geometrical information contained within the CAD file is used by the STEP-NC process planner to create a functional workplan. The plan is generated by the identification and handling of feature interactions. In the cases where the final resource specific NC file is feature based, it is possible to include the geometry information in the data structure as well. After the workingsteps required to manufacture the part are generated by the STEP-NC interoperable process planner they are saved in the process plan that will be used by the STEP-NC interpreter to generate machine specific NC files.

Tools and their relevant feeds and speeds can be specified in the STEP-NC interoperable process planner. This is however optional and if information is not present at this stage it will be automatically generated by the STEP-NC interpreter in the next phase.

While artificial intelligence can be applied to the whole process, the areas which will benefit most from having access to intelligence are the coupling points where information from one layer is used to generate the information contained within another layer. As illustrated in Figure 3, apart from these coupling points the information is merely translated or transported from one system to the next and therefore the potential benefits of applying intelligence are minimal.

[Insert Figure 4 about here]

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Figure 4 illustrates the three major coupling points between the layers where information in one layer is used to generate the information in the other layers. The first of these coupling points lies between the geometry layer and the workplan layer. This is where machining workingsteps required to manufacture each geometrical feature are identified intelligently and assigned to their respective feature. This is also where geometrical feature interactions are handled.

The second coupling point is where tools are assigned to individual workingsteps required to manufacture the component. The tools chosen from a database of valid tools for a specific operation can have some effects on the geometry, i.e. when the radius of the cutter dictates the minimum fillet radius of a feature. Furthermore the tools chosen for different workingsteps might make rearranging the workingsteps in the workplan necessary, i.e. to group workingsteps using the same tools in sequence. Tool feeds and speeds are also selected at this coupling point.

The final coupling point is where the information within the top three layers is utilised to generate machine axis movement instructions and NC switching instructions. Depending on the level of the intelligence of the CNC controller used to machine the component, this coupling point might be implemented partially in the controller.

4.2 Making manufacturing decisions based on historical data

To create a knowledge base that is useful for making intelligent decisions the semantics involved in information transformations in coupling points should be captured in machine understandable form. The knowledge base in the first coupling point for example will

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contain information on workingsteps required for generating each individual geometrical feature.

The basis for this knowledge is the foundation built by capturing historical data. During the initial runs of the process chain the system will be in learning mode and it will capture the decisions made by the user.

The system will record how the user chooses operations like drilling and reaming to create holes. As the system records data over time, it will gain confidence relating to the determination of workingsteps for geometrical features. When the preset confidence level is reached the system will start suggesting workingsteps to the user. If the user agrees with the choices the system makes, the confidence level is raised higher and upon reaching a certain level the system will make automatic decisions and will only inform the user.

Throughout the process the user will always have the choice to override a decision made by the intelligent system.

4.3 Using mobile agents to access knowledge-bases across the manufacturing enterprise

As shown by Allen et al. (2004) it is possible to employ multi agent systems at the first coupling point to make intelligent decisions based on a local knowledge framework. The above research presented a system that could intelligently identify feature interactions and decide upon an effective manufacturing order of the work plan.

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The same concept in the above research is applicable to the other two coupling points. It should however be noted that the coupling points do not necessarily reside on a single system. While some of the operations carried out in the coupling point are handled by one system the rest might be handled by another. For example, the tooling assignment for one feature might be handled in the interoperable STEP-NC process planner and the tooling assignments for the rest of the features in the same part in the STEP-NC interpreter.

As a result it is necessary to manage information across different parts of the system and different files. In cases where the STEP-NC manufacturing chain extends across the globe, the availability of remote information becomes a serious issue.

One solution to this problem is to maintain a central database where all the manufacturing information generated for all the coupling points throughout the system is consolidated. This database is then used as the information basis for intelligent decisions. While this solution might be initially easy to develop and deploy, it has the major disadvantage of requiring the entire information set to be transferred to one location. Furthermore each time a manufacturing decision is needed in a remote part of the company, all the relevant information should be transferred to that part of the company.

Mobile agents present an alternative solution. By using mobile agents it is possible to store manufacturing data locally where it is generated. The agents then traverse the company network according to their individual goals of making specific manufacturing decisions. They visit all the relevant data sources by transferring themselves to the systems containing

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the data sources and analyse the information contained within that data source in relation to the decision they are in the process of making.

If the information in one data source is not conclusive they move to another system and try to gather more knowledge to make the decision. Upon reaching the decision the agents migrate back to the originating system and implement the manufacturing decisions that they made. In case there is not enough information in the entire enterprise network to make the decision automatically, the agent will prompt the user for a decision and add that decision to the knowledgebase for future use.

Since the agents are much smaller in size than the knowledgebases transferring them instead of the data will not only lower the data transfer costs but will also reduce the time required to make the manufacturing decisions.

5. The mobile agent system prototype

A prototype mobile-agent system has been developed using Aglets to demonstrate the applicability of mobile-agent systems in achieving interoperability within the STEP-NC manufacturing context. The focus of the prototype system is the information coupling point between tooling and workingsteps. Namely the system has been designed to choose appropriate tools for the execution of workingsteps required to manufacture simple prismatic components.

[Insert Figure 5 about here]

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Figure 5 illustrates the overall framework for the Aglet based system. A CAD package generates the geometry for a component. The design is then passed on to the STEP-NC process planner which creates a machine independent process plan. This plan is saved in a STEP-NC file and is passed on to manufacturing venues around the world. In each subsidiary the plan is interpreted by a STEP-NC interpreter. When manufacturing decisions are needed, the Aglet server is instructed to create a mobile agent to gather the necessary information. The server has the network addresses of the other Aglet servers in the firm and if necessary has the capability to dispatch the agent to the other servers present.

The CAD/CAM system utilised is based on Integrated Platform for Process Planning and Control (IP^3AC), a rapid manufacturing application creation platform developed by the authors. This platform provides an object-oriented interface for accessing the information contained within the STEP-NC data structures.

[Insert Figure 6 about here]

Figure 6 shows the proposed system coping with a typical manufacturing decision. In this scenario a mobile agent is used to decide which tool should be used for creating a hole. This decision is made at the interpretation stage and while the STEP-NC interpreter working at a subsidiary of a manufacturing company is trying to produce a component.

In the first stage, the agent identifies the type of the workingstep. In the second stage, the agent looks up similar workingstep information on the local STEP-NC interpreter database

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. If the agent is not satisfied with the confidence level achieved by searching through the local data, it traverses to the third stage, which is the knowledgebase in the company's head office. The agent gathers enough information to derive a list of suggestions to the user and in the fourth and the final stage migrates back to the originating system. The tooling information is then linked with the manufacturing workingstep responsible for creating the hole.

[Insert Figure 7 about here]

Figure 7 shows the STEP-NC interpreter interface at the beginning of the first stage where the operator is asked whether an agent should search the rest of the network or if the operator will provide the tooling information for the feature in question.

[Insert Figure 8 about here]

[Insert Figure 9 about here]

Figure 8 and Figure 9 show screenshots of the Aglet servers. Figure 8 illustrates the Aglet server on the subsidiary computer system at work throughout the four stages. In the first stage the agent is created. In the Second stage local manufacturing data is searched and due to lack of confidence, another server on the network is chosen for migration. In stage three the agent has migrated and therefore no agents are shown on the subsidiary Aglet list. In stage four the agent has returned along with the manufacturing information.

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Figure 9 focuses on the Aglet server at the head office computer system. In stages one and two there are no agents present on the system. In stage three the agent from the satellite venue arrives and searches the knowledgebase. The screenshot of stage four shows that the agent has been dispatched back to its home after gathering the necessary data.

6. Conclusions

• The current decentralising trend of manufacturing companies causes these enterprises to migrate to distributed computer systems. To make these systems capable of making decisions or assisting human users in making manufacturing decisions it is necessary to implement intelligence in them. Distributed artificial intelligence is capable of handling distributed data sources efficiently and as a result has significant potential for adding intelligence to distributed computer systems.

• Multi-Agent systems and mobile agent systems as practical implementations of distributed artificial intelligence can be used to add intelligence in systems where data is stored in numerous locations.

• Aglets platform provides an easy-to-use library which can be used to create mobile agent systems along with messaging mechanisms rapidly.

• STEP-NC files with their layers of manufacturing information demonstrate the potential for interoperable systems. This potential can be realised with the addition of artificial intelligence. With sufficient artificial intelligence it is possible to create a manufacturing

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network where a design can be manufactured around the world identically by using various resources.

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Table 1. Software agent typology proposed by Nwana (1996)

Software Agent Type	Description
Collaborative agents	Autonomy and cooperation are the main characteristics. Learning might be present but is not the main emphasis.
Interface agents	Learning and autonomy are the main focuses.
Mobile agents	Agents capable of migrating to different parts of a computer network to achieve their function.
Information agents	Manage and gather information from many data sources.
Reactive Agents	Agents that only respond to a specific stimulus and are not generally aware of their environment.
Hybrid agents	Agents that have a combination of above mentioned abilities.
Heterogeneous Agents	Integrated set of different kinds of agents that can function together. Some agents might be hybrid agents.
Smart Agents	Agents that have a grasp of reality and can make decisions while adapting to the changing environment. Impossible to distinguish with a human element. Nwana believes that these agents are just aspirations of researchers and do not exist in reality.

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Figure 1

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```
ERROR: invalidaccess
OFFENDING COMMAND: --filter--

STACK:

/LZWDecode
-filestream-
[120 0 0 -138 0 138 ]
true
138
120
-savelevel-
```

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