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Adaptive Simplified Fuzzy Logic Controller for Depth Control of Underwater Remotely Operated Vehicle

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A Remotely Operated Vehicle (ROV) is one class of the unmanned underwater vehicles that is tethered, unoccupied, highly manoeuvrable, and operated by a person on a platform on water surface. For depth control of ROV, an occurrence of overshoot in the system response is highly dangerous. Clearly an overshoot in the ROV vertical trajectory may cause damages to both the ROV and the inspected structure. Maintaining the position of a small scale ROV within its working area is difficult even for experienced ROV pilots, especially in the presence of underwater currents and waves. This project, focuses on controlling the ROV vertical trajectory as the ROV tries to remain stationary on the desired depth and having its overshoot, rise time and settling time minimized. This project begins empirical modelling to capture the dynamics of a newly fabricated ROV, followed by an intelligent controller design for depth control of ROV based on the Single Input Fuzzy Logic Controller (SIFLC). The parameters of the SIFLC were tuned by an improved Particle Swarm Optimization (PSO) algorithm. A novel adaptive technique called the Adaptive Simplified Fuzzy Logic Controller (ASFLC) was introduced that has the ability to adapt its parameters depending on the depth set point used. The algorithm was verified in MATLAB® Simulink platform. Then, verified algorithms were tested on an actual prototype ROV in a water tank. Results show it was found that the technique can effectively control the depth of ROV with no overshoot and having its settling time minimized.

[**Keywords:** Adaptive simplified fuzzy logic controller, depth control, remotely operated vehicle]

Introduction

The control system of an ROV is an interesting and challenging problem. This is primarily due to the difficult and unpredictable environmental conditions that existed underwater[1]. During operation, the ROV undergoes a complex multi-axis motion trajectories that are highly nonlinear because the subsystems in the ROV are ill-defined and strongly coupled with one another[2]. Furthermore, the ROV dynamics can change considerably with the changes in surrounding conditions and external disturbances (e.g. wind velocity, ocean currents and waves) [3]. The hydrodynamic coefficients are difficult to measure or predict accurately[4]. Effective control schemes require relevant signals in order to accomplish the desired positions and velocities for the ROV. Designing a suitable controlling method of the ROV is challenging due to the unpredictable nature of underwater dynamics and difficulty in measuring ROV parameters[5]. In this research, the focused area was controlling an ROV in a heave-axis motion trajectory sometimes called depth motion to maintain its desired position. The function of heave-axis motion is to maintain the ROV position at a specific depth and ensuring its stability, which is also called station keeping or auto-depth control. This auto- depth control approach is used to maintain a position in relation to other moving ROV as it tries to remain stationary at a certain depth in automatic control after this depth is set by the operator.

Significance of the Research

The problem statement was found after a lot of investigations done in recent and existing works and several case studies based on journals, conference papers, thesis, books and other literature. In this research, the major problem considered in the ROV is in designing its depth control system. All Unmanned Underwater Vehicle (UUV) faced the same problem when controlling the vehicle since underwater environment is unexpected and unpredictable. As the scope of study is limited to the control system for station keeping (depth control), the other problems will not be discussed further except in future work's recommendation. The aim of this project is more on controlling an ROV to maintain its depth.

In most ROV, its pitch and roll motion are stabilized through the inherent hydrostatic characteristic of the construction itself. The control system should deal only with the depth, *z-axis*, the Cartesian positions *x*- and *y-axis*, and with the yaw angle. In general the uncontrolled angles for roll and pitch motions remain small and the depth can be decoupled from the other coordinates[6]. Maintaining the position of the small scale ROV within the working area is a difficult task especially in the presence of underwater currents, wave and wind even for experienced pilots[6]. ROV has been designed to be passively stable in pitch and roll (its centre of gravity is below the centre of buoyancy). For this reason, rolling and pitching motion of the ROV are very small, and therefore better results are obtained with a similarity motion model.

The function of depth control is to maintain the ROV position at a specific depth and ensuring its stability, which is also called station keeping mode. For depth control, overshoot in the system response will be one of the issues occurred because overshoot is particularly dangerous for the ROV in its vertical trajectory and may cause damages to both the ROV and the inspected structure. Overshoot reduction is actually achieved at the expense of increased rise time[7]. In general, the control objective is to obtain a limited or no overshoot in system response without penalizing the rise time. This is difficult to achieve since normally, the limitation of overshoot in system response can be obtained but the rise time will be slower. From the review of existing works, there seems to be very few literatures that look at optimizing ROV controller parameters at different operating conditions and then derive an adaptation law for the ROV to allow automatic change of optimum sets of parameters depending on different situations. One main motivation of this research is in the areas of optimization and adaptation of controller parameters. Adapting the optimized ROV controller parameters at different set point conditions may very well improve its performance in terms of reducing its overshoot and response time for depth control. This seems a problem worthy of further investigation.

The derivation of mathematical model of a UUV is a complex problem. It is difficult to delimitate or calculate many parameters, which has to be well known to solve the dynamic equations of UUV movement. Accurate dynamic model are crucial to the realization of ROV simulators, precision autopilots and for prediction of performances. Control of underwater vehicles is not easy, mainly due to the nonlinear and coupled characters of plant equations and also the lack of precise models of underwater vehicle hydrodynamics and uncertainty parameters, as well as the appearance of environmental disturbances [8] such as wind, current and wave. Many of the researchers have to ignore some uncertainties in the parameters to reduce the difficulty in designing the controller. The assumptions on the dynamics of ROV in deriving its mathematical model are the most common approach. Implementation of the controller on the ROV using FLC itself poses its own level of complexity. Consequently, implementation of FLC also demands for fast and high-performance processors. For SIFLC approach, there are many parameters to be tuned manually in the literature[9]. Trial an error method will be used to find the optimum parameter. In [9], the parameters has been reduced to two, to be tuned manually using trial and error. Consequently, it will take more execution time to find the optimum parameters. Another issue is that the SIFLC has never been tested experimentally on any UUV.

Depth Control of the ROV

The depth control approach is used to maintain a position of the ROV as it tries to remain stationary at a depth set point. For depth control, overshoot in the system response will be one of the issues to be considered because overshoot in the system response is particularly dangerous. Clearly overshoot in the ROV vertical trajectory may cause damages to both the ROV and the inspected structure. In order to meet the requirements of control systems for underwater robots, various types of control schemes are implemented in the literatures where the focus was on depth control method.

In [10,11,12,13,14] explain the depth control or heave motion applied for unmanned underwater vehicle such as autonomous underwater vehicle (AUV) and deep submergence rescue vehicle model (DSRV). In [6] and [15,16, 17, 18, 19, 20], discussion for depth control of ROV systems was done. The control method applied generally started from conventional controller such as PD and PID[20]. Then followed by an artificial intelligence approaches have been widely used recently in the field of underwater robots[12,13,14,15,16,17,18,19,20]. Some studies applying fuzzy logic controller (FLC) to underwater robots can be found in [15,17,20]. Implementing artificial neural network (ANN) methods to underwater robots control are also reported [10]. The different control techniques discussed have most commonly been used in combination with each other. Some types of combinations between fuzzy logic controller and conventional PID controller[11] and or combined with sliding mode control have been reported in [6,14,21]. Also combination between three or more types of controller such in [22] used PD, FLC, adaptive and sliding mode control and in [18] combine between adaptive, fuzzy logic and sliding mode controller. In [9,23,24] the authors used single input fuzzy logic controller (SIFLC) to control heave motion of a DSRV Model. The SIFLC offers significant reduction in rule inferences and simplify the tuning of control parameters. Practically it can be easily implemented by a look-up table using a low cost microprocessor due its signed distance method and piecewise linear control surface. The result indicates that SIFLC requires very minimum tuning effort and its execution time is in the orders of two magnitudes less than CFLC. In [12] the authors designed the control system of AUV for depth control and heading angle. The controller used is a sliding mode control using estimated hydrodynamics coefficients were estimated employing conventional nonlinear observer techniques such as sliding mode observer and extended kalman filter. This control algorithm makes the control system stable and accurately follows the desired depth in presence of parameter uncertainty. In [13] the authors explained the method to tune the scaling factors of fuzzy logic controller (FLC). This method used a radial basis function metamodel for optimising the UUV depth controller parameters. The model of UUV also used deep submergence rescue vehicle model (DSRV). Authors also did comparison between genetic algorithm (GA) and metamodelling where they showed that metamodelling managed to optimise the parameters in a much shorter time compared to GA. In [14] the authors designed the control system of the AUV. The authors used 6DOF for AUV. The control algorithm is adaptive in the dynamic parameter where this controller has been successfully implemented and experimentally validated on Omni-directional intelligent navigator (ODIN) platform and the experimental results showed good performances of the adaptive controller within constraints of the sensory system.

In [16] the authors used the ROV in the exploitation of combustible gas deposits at great water depths. The authors used fault-tolerant control scheme for an underwater ROV. The actuator failure tolerant scheme is composed by the usual modules detection, isolation, and accommodation of faults by control reconfiguration. The fault identification module is based on sliding mode control. In [17] the authors used fuzzy-PID controller method based on overshoot prediction to control the ROV for depth regulation. When ROV working in shallow water, the inevitable surge will impact them, resulting in errors in the depth of control affecting its normal operation. This method where fuzzy controller calculates the PID controller parameters, and then the underwater vehicle completes the fast and non-overshoot depth control of the ROV. The simulation results show that the method is effective and feasible. In [18] the authors designed the control system of ROV for depth control using adaptive fuzzy sliding mode control (SMC) approach. The authors used SMC enhanced by an adaptive fuzzy algorithm for the depth control of ROVs. In [19] the authors treat the ROV dynamics as a dynamic gray-box model and its uncertain parameters are identified from real data. A Proportional controller is used on the Gaymarine Pluto–Gigas ROV. The analysis of such a model shows that the nonlinear dynamics of the ROV contains a limit cycle. This discovery explains the observed oscillatory behaviour. An interesting aspect of this limit-cycling behaviour is that it is not due (as usual) to saturation effects of the actuators, but is intrinsic in the ROV dynamics. In [20] the authors designed the control system of an ROV for depth control. When the ROV control in a complex environment, improving the response speed and overshoot suppression is the most important. The authors used combination between proportional integral and derivative (PID) controller and fuzzy techniques to control the depth of the ROV. This author also showed the results have managed to reduce the overshoot in the depth response. In [6] the authors designed the control system of an ROV for position control. The authors designed a robust control system through the use of sliding mode or variable structure controllers. This author also models the hydrodynamics effects model on the vehicle and on the umbilical cable using Marison equation. The effect of the umbilical cable slows down the whole motion. This is due to the relatively high stiffness of the cable.

Critical Review of the ROV Depth Control

From the review of existing works, it seems that a lot of work in depth control of ROV has been done [19,20,21]. However, understanding the non-linearity of the dynamics of an ROV, its optimum controller parameters should be different at different operating conditions. For depth control, there seems to be very few existing works that look at optimising ROV controller parameters at different operating conditions and then derive an adaptation law for the ROV to allow automatic change of optimum sets of parameters depending on different situations. For instance, in [25], a standard PID controller was used whereby its parameters where only tuned once using MATLAB® PID tuner algorithm and only for one set point. In another example [20], they used an adaptive PID controller on an AUV (not ROV). However, they did not optimize their PID on the different set points to be used by the AUV. Instead, their adaptive rule comes from a complicated 3-input 1-output fuzzy controller. This may affect their algorithm implementation wise which they did not study. Therefore, at this point, one motivation of this research will be in the areas of optimisation and adaptation of controller parameters; focusing on simplified intelligent ones for fast real time application. Adapting the optimized ROV controller parameters at different set point conditions may very well improve its performance in terms of reducing its overshoot and response time for depth control. This seems a problem worthy of further investigation.

Methodology

Figure 1 shows the flow chart of research methodology. It involves of three stages such as literature review, modelling, and controller design. At the first stage, literature review was done on current and recent works and case studies of selected journal are studied to find the problem statement. At the same time the basic and fundamental theory of ROV (e.g. coordinate system, factors affect the design of the ROV, control system, and also modelling of the ROV) should be studied.

In the second stage, this project begins with hardware implementation where the thrusters and prototype of ROV with 4DOF were designed. The drawing of the ROV prototype was using the Solidwork's software to obtain parameters that will be useful in modelling of the ROV. The development and modelling of thrusters and low cost ROV for depth control using system identification technique via MATLAB® were described in detail in this paper. In this paper, mathematical dynamic modelling of the ROV was also described in detail. The comparison of ROV models obtained using between mathematical derivation and system identification is discussed within this paper.

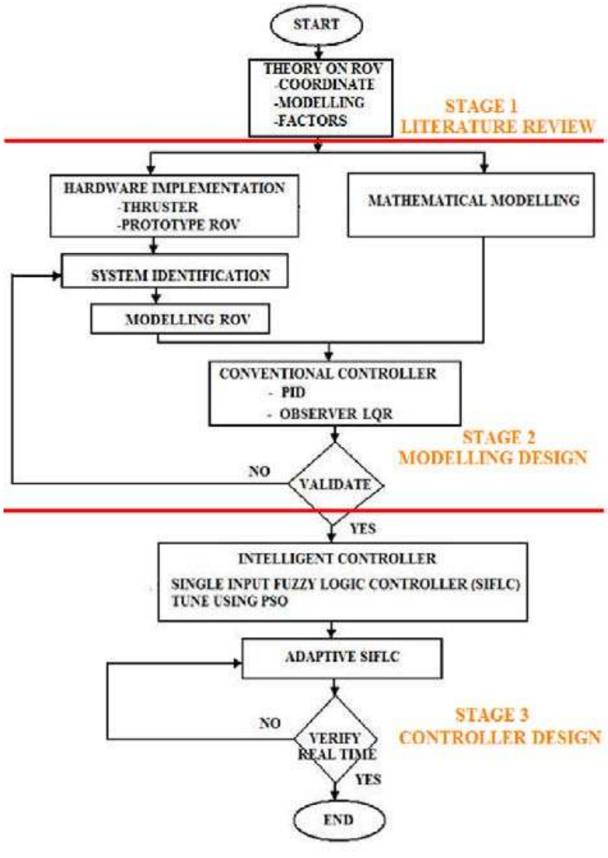


Fig.1– The flow chart of research methodology

The ROV design can be considered to be reasonably symmetric about its three planes. By making this assumption, several terms in the dynamic model matrices can be eliminated without serious loss of information. Symmetry also has an important implication for the coupling of the degrees of freedom as shown in Figure 2. It is straightforward assumed symmetry based on the ROV drawing using Solidworks^{TM} software to verify the following two cases (refer *z* and *x*-axis) as shown in Figure 3:

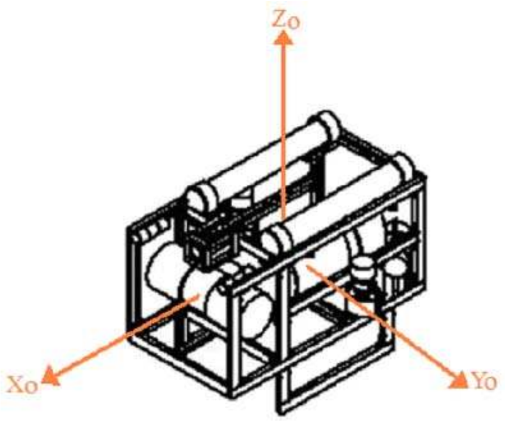


Fig. 2 –Symmetrical view using Solidworks software

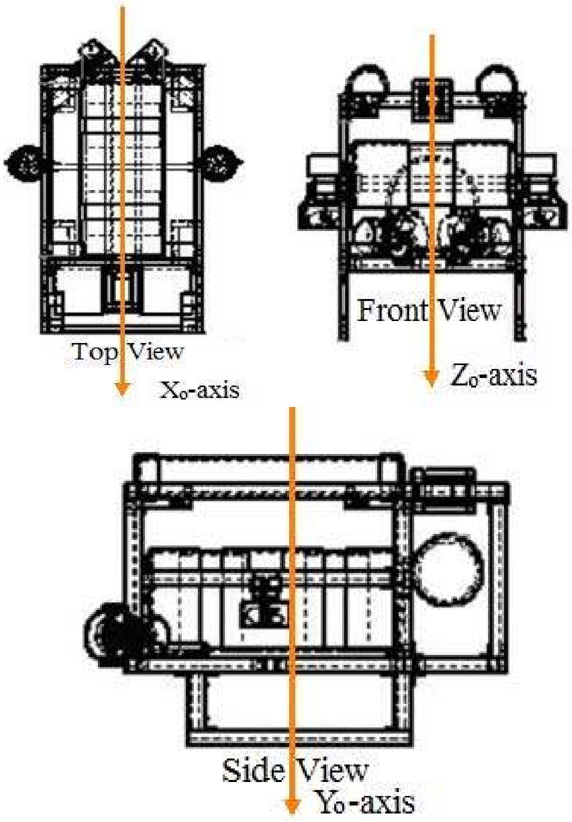


Fig. 3 –View for every axis

Conventional PID Controller

The model obtained in transfer function as discussed in results section was used in feedback control system design as shown in Figure 4. Figure 4 shows the ROV model used in a feedback control systems where the ROV's model obtained from the system identification toolbox and mathematical modelling. The first designed controller was by using the proportional controller. The improvement of the controller can be made by an addition of an integral and derivative controller to further improve the system. However, the design should be kept as simple as possible. The controller design was based on the conventional PID controller method. Simple control techniques (e.g. PID controller) have been more commonly used because of the relative ease of implementation. The comparison between system identification and mathematical modelling based on the same parameter of PID controller as shown in Figure 4.

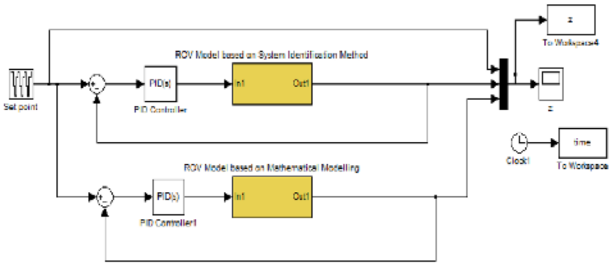


Fig. 4 – The both ROV models tested using PID controller on MATLAB® Simulink

Intelligent Controller Design

In stage 3 on research methodology that is controller design based on an intelligent controller will be studied as shown in Figure 5. In this research, the investigation will focus more on the Single Input Fuzzy Logic Controller (SIFLC). SIFLC method was inspired from the Conventional Fuzzy Logic Controller (CFLC) based on the signed distance method and piecewise linear control surface method [23,24]. The CFLC for Multiple Input Single Output (MISO) system of the rule base is simplified into a Single Input Single Output (SISO) system using SIFLC. SIFLC is a reduced number of control matrix rules and is uncomplicated to be implemented in real time application. CFLC for 7 x 7 control matrix rules are simplified into a single input with 7 rules proposed by [23]. SIFLC provides a simpler method for design of FLC, where the will be only one input variable, the rule table in 1-D space, a number of tuning greatly decreased, the computational complexity is mitigated. An improved SIFLC will be introduced to simplify the SIFLC. Then the parameter of an improved SIFLC will be tune using PSO techniques to find the most optimal parameter which will be discussed in detail in the next section. The improved SIFLC is a goal to ensure zero overshoot and faster settling time or at least minimum error in step response at the desired depth. A comparison study using conventional PID controller, PI controller, Neural Network Predictive Control (NNPC) and Observer-based output feedback control is also discussed in the next chapter to claim that improvement has been made on SIFLC and has given better results than others. A novel technique will be introduced in this research called Adaptive Simplified Fuzzy Logic Controller (ASFLC). The details of ASFLC will be discussed. Then, ASFLC will be verified on real time systems and also applied on others ROV with the same class. The whole processes on stage 3 for intelligent control design called as Adaptive Simplified Fuzzy Logic Controller (ASFLC) as the title of this research as shown in Figure 5.

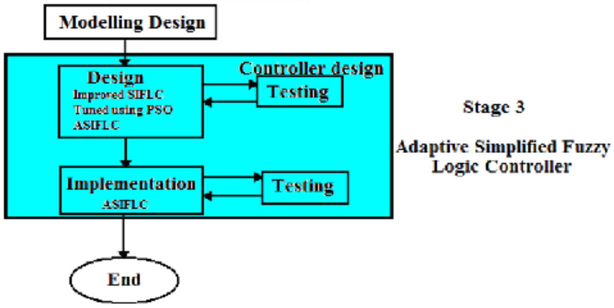


Fig. 5 –Stage 3 (controller design) of the ROV

An Improved SIFLC Tuning using Particle Swarm Optimization (PSO)

In this chapter, particle swarm optimization (PSO) algorithm is applied to tune a parameter of SIFLC for depth control of the ROV. An improved PSO algorithm based on a priority-based fitness PSO (PFPSO) and binary priority-based fitness PSO (BPFPSO) approach is employed for finding the optimal SIFLC parameters. Two parameters of SIFLC to be tuned namely the break point and slope for the linear approximation is considered to be tuned based on off-line results of the PSO algorithm to give a better system response. The parameters of SIFLC in [9,23,25], still need to be adjusted manually. A considerable design time is required to determine the optimum combinations of these two parameter values. Therefore, PSO can be used to assist the tuning process to reduce design time where this is one of the contribution to this research. SIFLC parameter tuning using an improved PSO algorithm for ROV has not been reported in the literature as of the day this thesis was written. The comparison between the two parameter values with the improved PSO algorithm as stated above is also examined. The simulation is accomplished within MATLAB®, Simulink environment to validate the performance of the SIFLC using tuned parameter.

An Improved PSO

An improved PSO algorithm based on a priority-based fitness PSO (PFPSO) and binary priority-based fitness PSO (BPFPSO) approach is employed for finding the optimal SIFLC parameters. This PSO algorithm is adapted from [26] but the authors implemented this algorithm for tune parameter of the conventional PID controller to control nonlinear gantry. Based on the control objective in this research, overshoot, OS is set as the highest priority, followed by settling time, Ts and steady-state error, e_{ss}. The control objective is to develop an improved SIFLC that can pledge to eliminate overshoot in the system response. For vertical trajectory, overshoot in the system response is predominantly risky because an overshoot in the depth control may cause damages to both ROVs and the inspected structure such as operating in cluttered environments.

Adaptive Simplified Fuzzy Logic Controller (ASFLC)

This section presented a new technique named as an adaptive simplified fuzzy logic controller (ASFLC). ASFLC design is used for depth control of the ROV. The inspired word a*daptive* comes from the concept of adaptive controller where it adapts the parameters continuously to put up relatively slow changes in the dynamic process and environmental disturbances as was explained by [27]. Adaptive controller can be applied both to feedback and feed-forward control parameters. There are two classes of adaptive controllers based on direct and indirect methods. In direct methods, controller parameters are adjusted directly from data measured during closed-loop operation, for example closed-loop model reference adaptive control by [27]. In indirect methods, first process model parameters are determined on-line by recursive parameter estimation and the control parameters are derived from the process parameter estimation, such as self-tuning regulator [28]. In this research, the direct methods are used, where the controller parameters of the SIFLC are adjusted directly from the data obtained during closed-loop operation of an improved PSO algorithm as described in the previous chapter. The optimum parameter for SIFLC was tuned using an improved PSO based on priority-based fitness approach is implemented for finding optimal SIFLC parameters.

ASFLC technique works by combining different settings of SIFLC that was optimized earlier using improved PSO algorithm. The optimum parameter for every case is used to test the ROV on different set points to prove that the obtained parameter can be adapted to the changing set point. The adaptation of different set point based on previous optimum parameter tuned by an improved PSO algorithm gives another contribution of this project. The implementation of this phase is verified through the MATLAB® Simulink platform. The biggest advantage of this method is it simplified the simulation and can be implemented without difficulty in a real time experiment. Once the simulation is simplified, the time execution is also improved.

The advantages of adaptive control are possible operation ranges can be increased and nonlinearities due to parameter changes can be eliminated or reduced. Adaptive control is also useful because ROVs are usually refitted with new equipment or devices such as a manipulator or vision system and adapted for different missions which change their static and dynamic characteristics. While the drawback is it needs enough excitation otherwise there might be a windup problem in parameter estimation [27]. The adaptation loop must be slower than control loop and usually leads to nonlinear observer problems. Proof of stability is difficult, especially in case of changing process parameters.

After several experiments on SIFLC which was explained in detail in this section the new method is introduced as adaptive simplified fuzzy logic controller (ASFLC). This ASFLC is used to control the ROV by following certain depth and maintain its position where the controller service is to stabilize the ROV at a certain depth. Figure 6 shows the simulation of ASFLC that applied to control the depth of ROV based on the determined set point. The control objective is to design a controller that can guarantee the limitations of overshoot in the system response. In this research, overshoot, OS is set as the highest priority, followed by settling time, T_s and steady state error, e_{ss}.

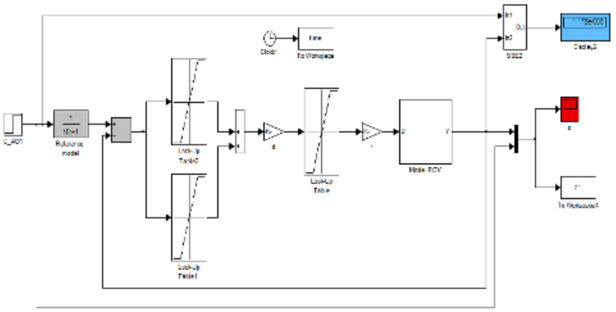


Fig. 6 – ASFLC is applied to control the ROV

Figure 7 shows the simulation of SIFLC for ROV model using MATLAB® Simulink. The simulation focused on depth control because the model of the ROV was obtained from the system identification method. As seen in Figure 7, the input signal is set with a different set point, so that the changing of input signal parameter affects the optimal parameter obtained by an improved PSO algorithm. In this research, the results show the different set point with different parameter tuned by PSO algorithm. Figure 7 shows the adaptive simplified fuzzy logic controller (ASFLC) in MATLAB® Simulink.

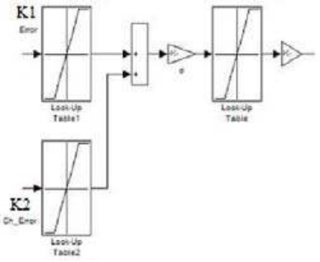


Fig. 7 – Adaptive Simplified Fuzzy Logic Controller

ASFLC is applied to control the ROV with a presence of uncertainties or disturbances. In this disturbance, the assumption comes from environmental disturbances such as waves (wind generated), ocean currents and wind. In general, these disturbances can be represented as both additive or multiplication to the dynamics equation of motion as presented in Figure 8. The environmental disturbances are modelled using wave model in [24], which introduced a damping term in the wave model to better fit the shape of PM-spectrum Pierson and Moskowitz in [27] and wave model plotted as shown in Figure 9.

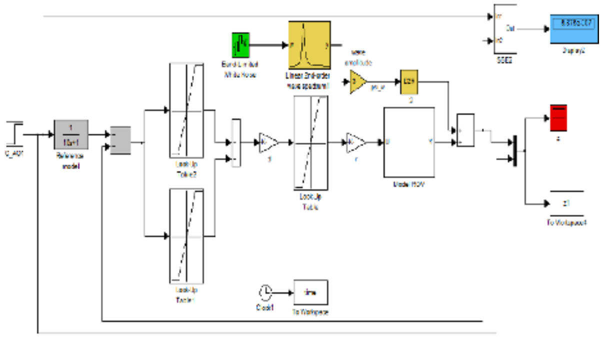


Fig. 8 –ASFLC controller block diagram for depth control with the presence of environmental disturbances

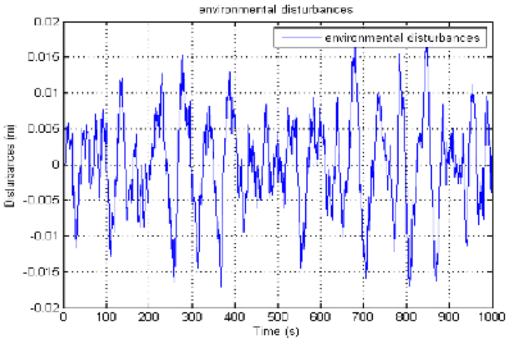


Fig. 9 –Environmental disturbances

The circuit was shown in Figure 10 used to test the ASIFLC algorithm. The actual depth control test took place in the laboratory tank test in Underwater Laboratory at University of Technical Malaysia Malacca (UTeM). The limitation for depth testing is that the tank is only 1.5 meter deep. Hence, only 1 and 0.5 meters of depth was used for testing to get a clear view of ROV depth. Based on the previous section, it explains the simulation and real time application using Microbox 2000/2000C, but in this research, it only considered using a low-cost microprocessor for more simplicity and easier implementation in real time. The microprocessor used is PIC 16F877A. The output is the motor thrusters that controls the depth of ROV based on set point. The feedback is taken from the pressure sensor to give signal to control and follow the set point.

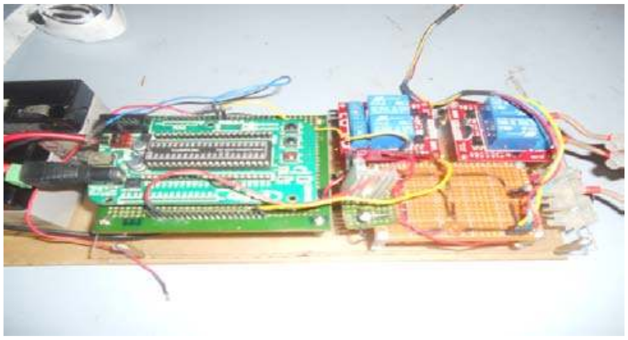


Fig. 10 – Electronic circuit for ROV depth control

The circuit for depth control of the ROV was tested using Proteus software as shown in Figure 11. This is important to know the algorithm used in this project, whether it can function well and giving the expected results. These circuits have two thrusters to control the depth of the ROV. Another motor is the motor pump for ballast tank. This motor is functional if the depth of the two thrusters had reached the saturation point. The controllers utilized a simple on-off control scheme and were used to test the pressure sensor for depth control. In this research, the ballast tank function is not considered. For simulation of circuit using ASIFLC, the Proteus software is used to check the complete circuit before implemented in hardware as shown in Figure 11.

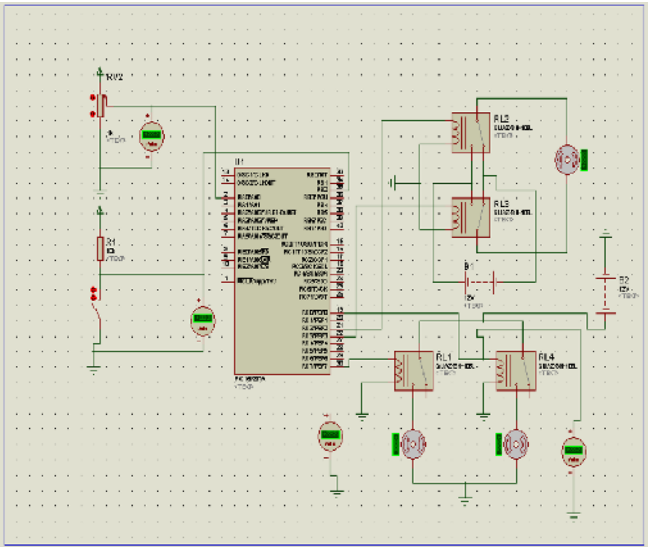


Fig. 11 – Auto- depth control with the PIC microcontroller using Proteus software

Results and Discussions

Hardware Implementations

Microbox 2000/2000C is a solution for prototyping, testing and developing real - time systems using standard PC hardware for running real-time applications as explained in [28], and as shown in Figure 12. Microbox 2000/2000C acts as a microcontroller, and is also called the “XPC target machine”. The result benefits the users in terms of cost and time saving, and makes the control system design and testing is easy to accomplish, and allowing flexibility when dealing with complex control systems as reported by [29]. Figure 13 shows Simulink block for Microbox interfacing with MATLAB®.

Fig. 12–Interfacing for Microbox 2000/2000C

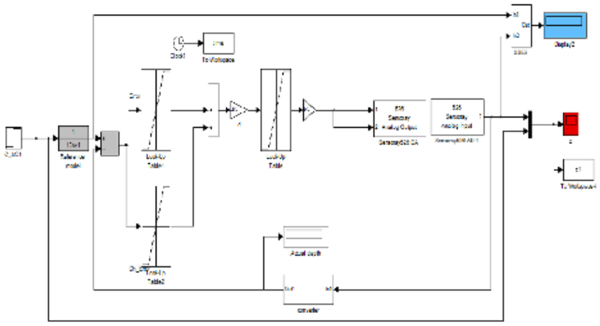


Fig 13–Simulink block for Microbox interfacing with MATLAB®.

Because of constraint on location of Microbox 2000/2000C, to implement ASFLC in real time application, low cost microprocessor will be used. This is one of advantages of ASFLC where it can easily be achieved with low cost microprocessor or microcontroller.

Transfer function state space technique yields:

$$TF = \frac{0.4871\ s^2 + 1.37\ s + 67.31}{s^3 + 4.911\ s^2 + 8.309\ s + 76.09} \qquad (1)$$

And the ROV system also can be written as continuous time-invariant as in Equation (2) and (3). By using MATLAB® command transfer function equation can change to state-space model as written in Equation (4).

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (2)$$

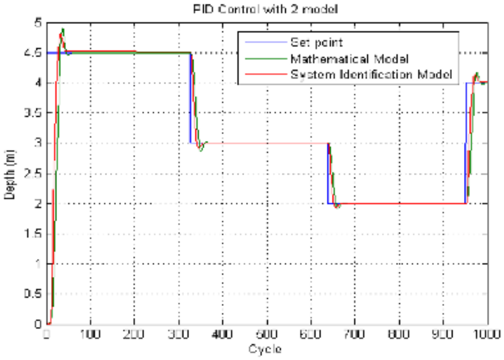
$$y(t) = Cx(t) + Du(t) \qquad (3)$$

$$\dot{x}(t) = \begin{bmatrix} -5.835 & -9.826 & -0.6262 \\ -285.8 & -159.3 & 588.9 \\ 286.8 & 87.12 & -326 \end{bmatrix} x(t) + \begin{bmatrix} 3.621 \\ -105.8 \\ 38.18 \end{bmatrix} u(t)$$
$$y(t) = \begin{bmatrix} 5.358 & 0.1272 & -0.02792 \end{bmatrix} x(t) \qquad (4)$$

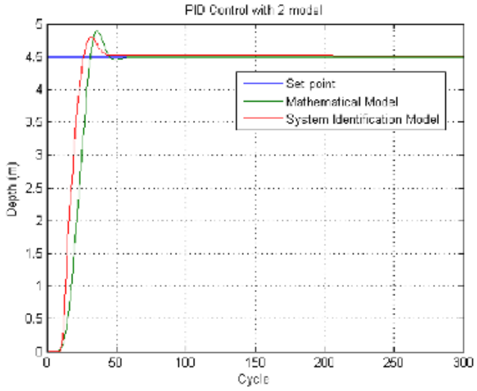
The model obtained from system identification technique will be analyse in terms of controllability and observability and also asymptotically stable. Based on Equation (4), the system is both controllable and observable because the system has a rank of 3. This system is asymptotically stable when all eigenvalues of *A* have negative real parts.

Table 1-PID parameter

Parameter	Proportional (P)	Integral (I)	Derivative (D)
Numerical value	2.2257	0.7839	0.1619



(a)



(b)

Fig. 14 – Comparison between mathematical models with system identification model

The response from the system based on the ROV model was acceptable. The comparison between mathematical models and system identification model as shown in Figure 14, which system identification model showed better results than mathematical modelling in terms of overshoot where the system identification model obtained 8.67% overshoot compared to mathematical modelling where almost 10% overshoot was obtained based on same parameter for PID controller as tabulated in Table 1. The system identification model seems to be more accurate since it include environmental disturbances when the experiment were conducted in laboratory tank test or in the pool. To eliminate this overshoot an intelligent controller will be applied where results on an improved single input fuzzy logic controller will be covered in the next section.

Parameter K_1 and K_2 from experiments are plotted in the graph and they behave like the linear equation as shown in Figure 15. Parameter K_2 obtained almost straight line and can be written as a linear equation while for the parameter K_1 is set to best fit line and written in a linear equation. Based on two linear lines obtained, they can be assumed like a signed-distance method that was used to simplify FLC into SIFLC as was discussed in [24]. Based on derivation of piecewise linear approximation method, [24] represent it as Look-up Table as shown in Table 2. The signed-distance method is tuned using PSO algorithm which represent as a lookup table as shown in Figure 15. The lookup table represented the parameter in the signed distance method. This method is helpful to implement in real time application because it is simple and easier to implement. Only linear equation or look-up table method is used as a controller for depth control of the ROV.

Table 2 - The results for different set point

	(a)	**(b)**	**(c)**	**(d)**
K_1	162.9447	177.4653	199.9354	87.8562
K_2	25.3974	24.1349	64.5831	9.8352
e_{ss}	0.0003	0.0003	0	0.0001

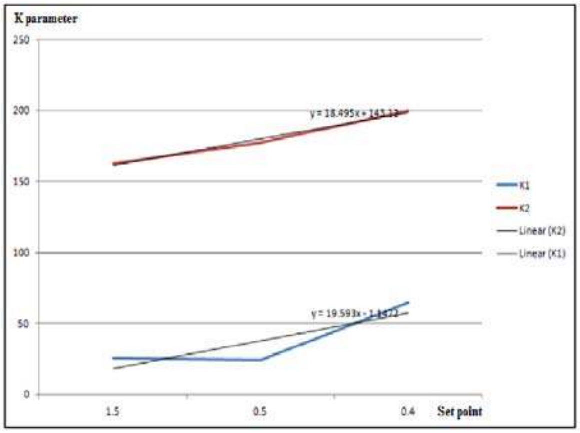
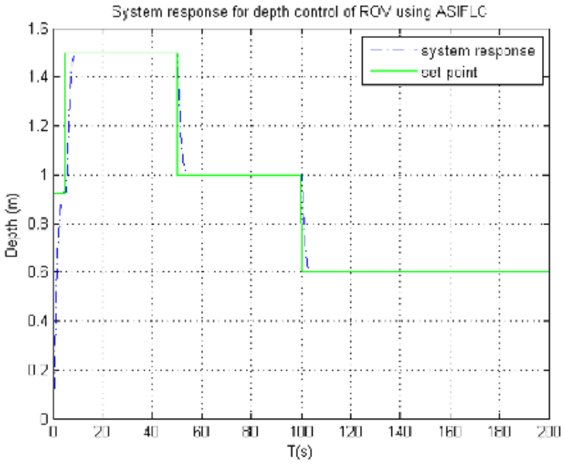
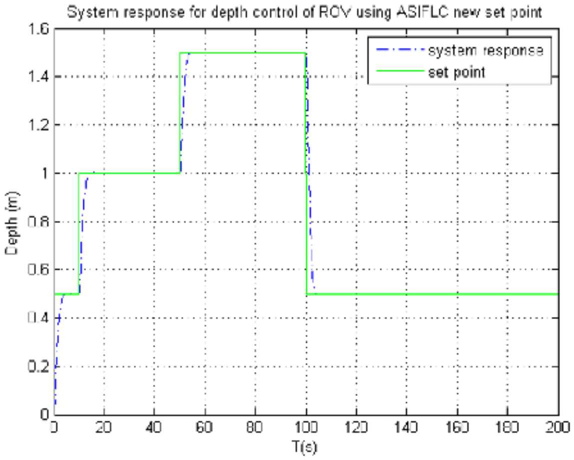


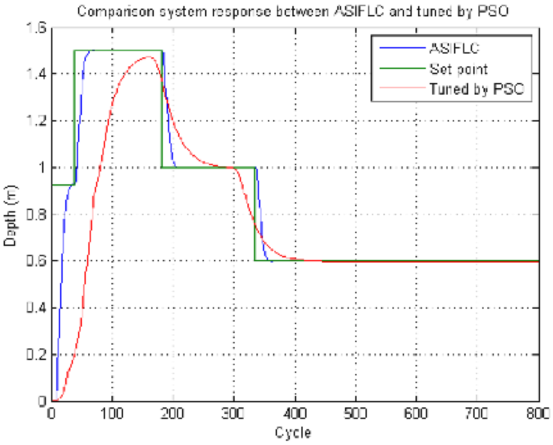
Fig. 15–Parameter K_1 and K_2 plotted in a linear equation



(a)



(b)



(c)

Fig. 16–System response for depth control of ROV using ASIFLC

Figure 16 (a) shows the result where the signed-distance method represented by a look-up table was used. This proposed method called as an ASFLC. This technique claims it gives the best performances in system response and can adapt to changes to the set point. As proved, another set point was also applied in this system for testing the proposed controller as shown in Figure 16 (b). It shows that, the ASFLC can adapt to set point changes effectively. Figure 16 (c) shows the comparison between ASIFLC and parameter tuned by PSO. The percentage of overshoot in the system response for ASIFLC in the presence of environmental disturbances is 0.46% as shown in Figure 17. The error is still low and can be accepted and ASIFLC seems to be robust even in the presence of disturbances.

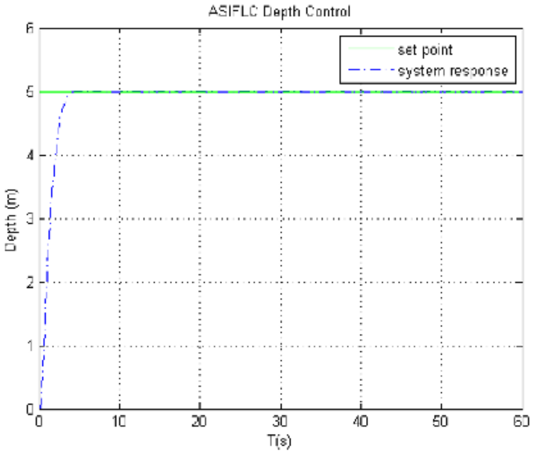


Fig. 17– System response of ASFLC with presence of environmental disturbances

Table 3: Comparing system performances of depth control for the ROV

Characteristics	**SIFLC**	**ASFLC**
Peak time, *Tp (s)*	66	10
Rise time, *Tr (s)*	30	5
Settling time, *Ts (s)*	66	10
Overshoot percentage (*%*)	0	0

Conclusion

In this research, SIFLC details were studied and used for the depth control of a remotely operated underwater vehicle (ROV). This research investigates the effect of tuning the variable parameter for SIFLC to improve the performances of system response for depth control. Improved SIFLC parameter for system response during the tuning process was based on factors that affect the performances of system response. The improvements can improve the performances on system response. These techniques have zero overshoot and steady-state error in step response at desired depth. The simulation revealed that the improved SIFLC has excellent performance and gives satisfactory results compared to conventional SIFLC and other controller types.

This project also investigated on using improved PSO to tune the parameters of SIFLC for depth control of the ROV. An improved PSO algorithm was implemented to find optimal SIFLC parameters. Two parameters of improved SIFLC were considered for tuning by an improved PSO algorithm based on off-line results. Finally, a new method called adaptive simplified fuzzy logic controller (ASFLC) for depth control of the ROV has been proposed and tested. The ASFLC has managed to utilize the different values of optimized SIFLC parameters to effectively accommodate the changes in the set point. The optimum parameter for each case was used to test different set points to prove that the parameter obtained can adapt to the changing set point. The adaptation of different set point based on the previous optimum parameters tuned by a PSO algorithm is a significant contribution to this project. The results were plotted and implemented using a linear equation or by a lookup table. Hence, ASFLC gave better performances in system response for depth control when the set-point is changing. The biggest advantage of this method is it simplified the simulation and can be implemented without difficulty in real time because it can easily be achieved using a low cost microprocessor or microcontroller and the time execution is also improved.

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