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Non-Intelligent and Intelligent Force Control for Robotic Applications: A Review

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This paper presents an overview of force control approaches for robotic systems. It covers three main methods: non-intelligent methods, intelligent methods, and recent methods. In each section, the discussion focused on how the researcher implements their methods in control system to obtain the desired force control for system's robustness towards external disturbances and internal uncertainties. The purpose of applying force control is to ensure that the executed robotic task does not damage the manipulated object or environment. The benefits for each method were highlighted at the end of each section.

Keywords: force control; intelligent control; non-intelligent control; robot control; artificial neural network; fuzzy logic

I. INTRODUCTION

Industrial robots have been developed parallel with the development of technology in instrumentation and control. Often robots are expected to provide dynamic and stable control system where robustness and adaptability towards the environment is a bonus. Task constraints in some degrees of freedom (DOF) often need a position or velocity control and in others force control. On top of the ability to control according to the specified parameters and applications, the challenge is on ensuring the stability and accuracy of the control where nonlinearities are inevitable for real dynamical robot systems.

Controlling the physical contacts between the robot and environment is essential to produce a more capable human-like robot. Thus, force control is becoming an important feature for robots due to the necessity of interaction with the object to be manipulated or the environment in the task. Recent demand requires robot manipulators to make decision on their own to change robot's motion according to the change in the associated object/environment or even when they face disturbances or uncertainties. Task planning errors and inaccuracy of sensor measurements may deviate the end effector from the commanded trajectory, which consequently may lead to damage to the robot itself or the environment. This brings up the importance of force control in producing a more human-like robot which responses towards the external effect acted on the robot.

Hybrid position/force control and impedance control are the two primary schemes adopted for force control. In brief, hybrid position/force control is assigned to control position and force along the unconstrained task direction and the constrained task direction, respectively. It is a widely implemented scheme of force control if detailed information of the environment is available. However, it is not easy to model an environment in most practical situations which involves unexpected uncertainties. Hybrid position/force control scheme could be used to distinguish the position-controlled and the force-controlled subspaces, but it is still difficult to produce the manipulator impedance (Anderson & Spong, 1988; Liu & Goldenberg, 1991; Patel *et al.,* 2009) involving interaction forces between the end effector and the environment. A survey on force control approaches by Yoshikawa (Yoshikawa, 2000) reported that hybrid control scheme does not consider the dynamics of the manipulator strictly, thus may cause an unstable response. Furthermore, it can be concluded that the lack of concern to the dynamics

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of manipulator could reduce the manipulating capability when the interaction force occurred. Realising the problem regarding the importance of dynamics relationship when contact force occurs between the robot and its environment, Hogan (Hogan, 1984) proposed a solution with impedance control which emphasises the significance of manipulator's dynamic behaviour to address the issue. It is suitable to control the interaction forces between object and end effector since its objective is to control the dynamic relationship between the force and position rather than just to control these variables alone (Hogan, 1984).

II. NON-INTELLIGENT METHOD

For the non-intelligent method section, the discussion will be focusing on how this method was used for force control. This section discusses two approaches which are sliding-mode and adaptive control.

A. Sliding Mode Control

Sliding mode control (SMC) is a method that allows a system to adjust the control signal by adjusting the gain of the system. It acts like a Proportional-integral-derivative (PID) control, where both need gain to be tuned. However, SMC requires the model equation of the system and commonly used for nonlinear systems. The advantages of SMC come from its fast response, good transient performance and robustness to parameter variations (Lian & Lin, 1998). The general procedure for SMC can be illustrated as in Figure 1.

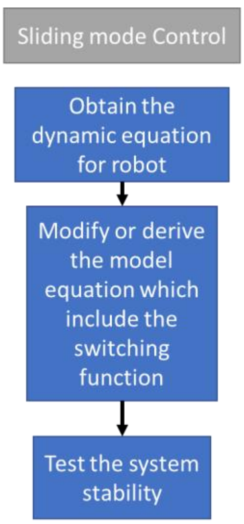

Figure 1. General flowchart for SMC method

Su, Leung and Zhou (Su, Leung & Zhou, 1992) proposed a sliding mode control to a constrained end effector of a rigid robot. Due to the constrained surface in the robot task, the method was designed to use a dynamic model with the reduced degree-of-freedom of the robot added with the constrained force. However, Grabbe and Bridges (Grabbe & Bridges, 1994) commented on this study that they should define a separate force control law and perform separate stability analysis for force tracking error. Furthermore, lack of information on force tracking analysis did not support the claim by (Su, Leung & Zhou, 1992) that the force tracking error was approaching zero.

Consequently, Lian and Lin (Lian & Lin, 1998) developed a sliding motion control and force control of constrained robots where the parameters were uncertain. The outcome of this study was also to improve the method by (Su, Leung & Zhou, 1992) based on the comments by (Grabbe & Bridges, 1994). This approach was introduced to solve the problem by incorporating motion-error variable and force-error variable. A simulation study was done to observe the controller performance on joint position, joint velocity and constraint forces. Under the specified force applied to the robot in the simulation test, the joint control tracked the desired trajectory well using the proposed method.

A study by Xu, Lu and Lv (Xu, Lu & Lv, 2019) proposed a high-gain observer-based sliding mode control (HOSMC) for a single-rod servo actuator. Sliding mode control was modified where the traditional sign function switching equation of SMC was replaced with a smooth and continuous function that represents the distance of the state from the sliding surface in order to eliminate the chattering problem. Simulation for HOSMC was done under two conditions, i.e., under uncertainties and without uncertainties, and the performance was compared to a proportional-integral observer-based backstepping controller (PIOBC) proposed by Nakkarat (Nakkarat & Kuntanapreeda, 2009). The results of the simulation showed that HOSMC outperformed PIOBC in tracking the desired force with faster response and quicker convergence.

In another study, sliding mode method was also used to design the impedance controller for an Intervention Autonomous Underwater Vehicle (I-AUV) (Dai *et al.,* 2020) which encounters nonlinearity problems from the system model and unknown fluid disturbances. The kinematic system was derived which includes the vehicle and the manipulator of the end effector used to control the end effector position, vehicle position and vehicle orientation. The total DOF is nine, six for the vehicle, and another three for the manipulator. The manipulator was attached to the vehicle, and the force sensor was placed at the end effector of the manipulator. The system has nine control inputs that include force and torque inputs for the vehicle and manipulator. SMC switching function was derived based on the dynamic model of I-AUV and the desired impedance model. The results of the simulation test showed that the system was capable of maintaining the desired 10N contact force output and producing good tracking performance with ±3 ×10-3 m error of position and orientation of the vehicle. In the experimental test, the vehicle was moved towards a wall with the manipulator extended to allow the end effector interacts with the wall. It was done with two sets of initial conditions for different positions, orientation, and desired contact force. In both conditions, the position and orientation of the vehicle have successfully moved the vehicle towards the wall with a significantly small Root Mean Square Error (RMSE). Meanwhile, the force control managed to maintain the desired contact force, although the overshoot of the system was quite high at around 5 N.

Beak and Kwon (Baek & Kwon, 2020) presented a paper on an adaptive sliding-mode control named as Strong and Stable Adaptive Sliding-mode Control (SS-SMC) with the objective of reducing the joint angle error. The work introduced two adaptive systems, namely the parent and the child adaptive laws. The values of the parent and child adaptive laws were used to calculate the switching gains of the SMC. The parent and the child adaptive laws are responsible to provide a fast adaptation rate and time-varying update parameters, respectively. A simulation test was done to compare SS-SMC with time-delay control (TDC) (Steve Hsia, Lasky & Guo, 1991) and an Adaptive Sliding-Mode control (ASMC) (Baek, Jin & Han, 2016). The result showed that the SS-SMC has the smallest RMSE in joint position compared to ASMC. Table 1 shows the summary of the studies on sliding mode method.

Table 1. Summary of studies on SMC method

References	**Methods in detail**
Su, Leung & Zhou, 1992	• Used Euler-lagrangian formulation with the absence of friction to obtain motion equation. • Used constraint force to obtain the sliding mode.
Lian & Lin, 1998	Control law considers the motion-error and force-error variables.
Xu, Lu & Lv, 2019	Used a continous function instead of sign function that considers the tracking error in the controller design.
Dai *et al.*, 2020	Switching function was derived based on the dynamic model of I-AUV and the desired impedance model.
Baek & Kwon, 2020	Two adaptive systems, namely the parent and the child adaptive laws were used to calculate the switching gains of the SMC

B. Adaptive Control

Adaptive control was known for its parameter estimator and robustness towards uncertainties and unknown disturbance with no prior or partial knowledge of the process control. There are two main adaptive controls which are model-reference adaptive control (MRAC) and self-tuning method. The flowchart in Figure 2 shows the general method in adaptive control.

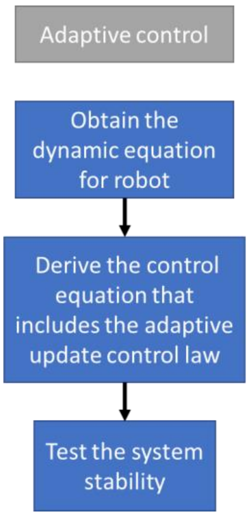

Figure 2. General flowchart for adaptive control method

A new adaptive impedance control was proposed by Duan *et al.* (2018) for force tracking, which has the capability to track dynamic desired force and compensate for uncertainties in the environment. The contact force of robot end effector was modelled and used as the feedback force of a position-based impedance controller which continuously tracks the dynamic desired force under random stiffness uncertainties. The adaptive variable impedance adjusts the impedance parameter online to reduce the force tracking error caused by unknown environment surface stiffness and dynamic environment location. The proposed approach compensates for the tracking error and the dynamic desired forces due to unknown environment. Simulation test was done to compare classical impedance control and adaptive variable impedance on four different environment surfaces, i.e., flat, slope, sine and complex surfaces. Similar experiments test were done on ESTURN ER16 industrial manipulator on flat, slope and curved surfaces. The results from both tests showed that the work could track the desired force accordingly and adapt to the dynamic desired force.

An explanation of the advantage and disadvantage of a new model-based adaptive controller compared to non-adaptive controller and non-model-based controller was done by Whitcomb *et al.* (1997). Three controllers used in this paper were Proportional-derivative force (PDF), Inverse Dynamic Critically Damped Force (IDCF) and Inverse Dynamic Critically Damped Force Adaptive (IDCFA). The control input for the PDF consists of the feedforward of the desired surface normal force, integral of the force error and, the proportional and derivative of position and velocity error feedback. Meanwhile, IDCF and IDCFA were designed using the derived sliding mode control equation based on Arimoto, Liu & Naniwa (1993). The control input equations for both occupied the plant dynamic equation with the same parameters used in PDF controller. However, in order to become an adaptive controller, IDCFA introduced an additional update law equation to the plant dynamics in the control input equation. These controllers were compared on the force performance by conducting an experiment test, which was implemented to observe the effect of the controllers on nine different conditions. The result showed that IDCFA outperformed in all different experimental setup which concluded that the robot system can be improved with the addition of an adaptive controller.

Research by Li & Ge (2014) proposed a method for an interaction between a robot arm and an unknown environment using a two-loop control framework using impedance learning. The impedance learning was used in the outer-loop control to update the impedance stiffness and damping parameters except for the mass for the robot. The cost function was used to reduce the position and velocity errors of the robot joints which then update the impedance parameters. In the inner-loop control, an adaptive position control applied PD-like gains on the position and velocity errors with the control input force obtained from the impedance learning to produce the joints' torque. The effectiveness of the adaptive control and impedance learning validity were simulated on a six-DOF PUMA560 model. The simulation test was implemented under the conditions of with or without the adaptive control while the impedance learning validity was verified by introducing different cost function values. The simulation results showed that the condition with the implementation of the proposed adaptive control was capable of reducing the tracking errors. Furthermore, the test result for the impedance learning validity showed that it could maintain the interaction force while updating the impedance parameter according to the uncertainties of the environment. Meanwhile, an experimental test on a developed robot by Ge *et al.* (2011) was used to validate the simulation result of the impedance learning with two different cost function values. Both experimental and simulation results showed the same stiffness behaviour of the robot for the different cost functions.

In another study, Arefinia *et al.* (2020) proposed a robust adaptive model reference impedance control of a robotic manipulator with actuator saturation. The researcher developed a new adaptive model approach that considered input saturation, the unknown bound of the force sensor measurement noise, the nonmeasurable acceleration and parameter uncertainties of a nonlinear robot manipulator using backstepping method to reduce the chattering problem. With all the considerations mentioned above, the system is integrated with an auxiliary system, bounded-gain-forgetting composite adaptation laws, adaptive bounding technique and first-order filter to overcome it. Simulations of the developed control system were divided into two experiments; first, to evaluate on two arms laparoscope robot (Sharifi, Behzadipour & Vossoughi, 2014) and second was to compare the proposed system with MIRC 4 (Slotine & Li, 1991). The results showed that the developed system could track the desired trajectory and have a faster convergence time.

Beak, Jin, and Han (Baek, Jin & Han, 2016) presented an adaptive sliding-mode scheme (ASCM) that uses time-delay estimation (TDE) and pole-placement control (PPC) methods. These methods were used to cancel the uncertainties from the feedback compensation and stabilise the linear system to reduce tracking error. A simulation to test the position of joints to follow the desired reference trajectory was done, and it was compared with two other controllers that were also using PPC (Plestan *et. al.,* 2013; Slotine & Li, 1991). The simulation results showed that the developed system's performance has lower tracking error with fast adaptation and less chattering effect than the previous study (Slotine & Li, 1991). However, this paper was commented by Su in (Su, 2020) where basic correction and improved ASCM correction was presented. Table 2 shows the summary of the studies on adaptive mode method.

Table 2. Summary of studies on adaptive control method

References	Methods in detail
Duan *et al.,* 2018	Adaptive variable impedance adjusts the impedance parameter online to reduce the force tracking error.
Whitcomb *et al.,* 1997	The adaptive controller developed based on the SMC equation by (Arimoto, Liu & Naniwa, 1993) employed the dynamics of the plant and the errors of position, velocity and force into the control input.
Li & Ge, 2014	The adaptive position control used a PD-like gain of the position and velocity errors with the control input force obtained from the iteratively updated impedance parameters.
Arefinia *et al.,* 2020	The adaptive technique used back stepping technique for the uncertain nonlinear dynamic of the robot manipulator with prediction error control.
Baek, Jin & Han, 2016	ASCM used TDE and PPC methods to cancel the uncertainties from the feedback compensation and stabilise the linear system to reduce the tracking error.

C. Benefits of Non-Intelligent Method

This section discusses the benefits of sliding mode control and adaptive control of the non-intelligent methods. Both methods were used for nonlinear model that faces control challenges from unknown environment problems, external disturbances and system's uncertainties. For both methods, the model of end effector or environment needs to be defined or derived. The derivation of both methods is usually based on dynamic equations and impedance control. These methods were proven to be robustness for some researches with the only limitation on the needs of recursive updates of system parameter.

III. INTELLIGENT METHOD

Intelligent force control is an idea to allow force control to learn and adapt. Cambridge dictionary defines the word intelligent as the ability to understand and learn well (Cambridge English Dictionary) while The Free Dictionary defines intelligent robot as a robot that functions as an intelligent machine; that is, it can be programmed to take actions or make choices based on input from sensor (The Free Dictionary). Intelligent controller should have the ability to identify the uncertainties of a plant and reduce the effect of state constraints through learning process. The most researched intelligent controllers include methods using Artificial Neural Network (ANN) and Fuzzy logic.

A. Artificial Neural Network

ANN is a method which has various approaches such as Recurrent Neural Network (RNN), Convolution Neural Network (CNN) and Radial basis Function (RBF) to approximate nonlinear functions. The basic structure of ANN contains input layer, output layer, hidden layer, neuron/node, weight, bias, activation function and learning function. Every type of ANN is different based on the arrangement and selection of the basic structure to suit the requirement of a control system. The general flowchart for ANN is shown in Figure 3.

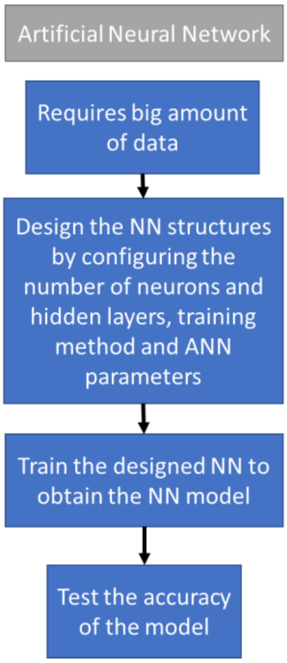

Figure 3. General flowchart for ANN method

Model-based predictive algorithm (MPA) and NN were proposed to an impedance-based force controller scheme of a PUMA 560 robot model (Baptista & Sa Da Costa, 2015). MPA is used to calculate the virtual position and velocity of the end effector based on predictive algorithm and actual force measurements to be as the input to the impedance controller. The NN was introduced to further compensate the force error by modifying the acceleration reference produced by the impedance controller, thus providing fine tracking of the robot motion in non-rigid environment. The input for the NN is the reference position vector over three consecutive sampling periods, while the output of the NN is the correction factor for the acceleration reference trajectory. The conventional online backpropagation used two layers consisting of a hidden layer with a node activation function of a hyperbolic tangent, and the output layer with the activation function of a linear type. Simulation results showed that the proposed method was able to maintain contact with a non-rigid friction contact surface with minimum environment's deformation and contact force error.

A study on neural network-based hybrid force/position control method was developed for a constrained rigid robot manipulator in the presence of uncertainties and external disturbances (Rani & Kumar, 2018). The control model contains model-based term, Radial Basis Function (RBF) NN and adaptive bound part. In order to obtain the desired force and position of the end effector, torque input control was developed using RBF to approximate the unknown dynamic equation. Besides that, an adaptive bound equation was derived to include the reconstructive error from RBF before applied into the controller's equation. The proposed controller was verified by Lyapunov function for the stability analysis of the system. Simulation results on the two-link robot manipulator showed that the end effector's controlled force rapidly tracked the desired value in the presence of friction and unknown external disturbances.

Research by Jung and Hsia (Jung & Hsia, 1998) proposed a solution employing the sense contact force and NN technique in controller's design for impedance force control, which considers the uncertainties in the robot dynamic and environment stiffness. There were two different approaches, Torque-based NN impedance control (TBNNIC) and position-based NN impedance control (PBNNIC). The outputs of each method were used to cancel the uncertainties caused by inaccurate robot model in the inverse dynamic model control. TBNNIC was designed to achieve disturbance rejection for impedance force control at the control input signal while PBNNIC compensates the system's reference trajectory. Two-layered feed-forward was used for the NN controller for both methods, consisting of input buffer, nonlinear hidden layer, and a linear output layer with a sigmoid activation function. Both controllers were simulated based on a three-link robot with two different tasks. The first task was flat sine-wave tracking with discontinuous environment stiffness profile, and the second task was circular tracking on a tilted environment with a continuous environment stiffness profile. The simulation test showed excellent results on the force tracking error and convergence rates for both results. However, the author claimed that PBNNIC has performed slightly better than TBNNIC in producing a more robust force control.

A different approach was proposed by Zhao *et al.* in (Zhao *et al.*, 2020) where a grasp prediction based on monocular depth images of object grasping by a manipulator robot was done using deep learning method. They proposed Grasp Prediction Network (GPNs) to predict candidate groups of grasp points and Grasp Evaluation Network (GENs) to evaluate the candidate groups' grasping quality. GPNs were designed based on Convolutional Neural Network (CNN) and Gaussian Mixture Model (GMM). The nonlinear image characteristic was introduced by applying a rectified linear unit (ReLU) activation function in the GPNs process. The grasp quality is described in terms of a force-closure metric where each group grasp point is correlated to a grasp quality. The same feature extractor was used for both GPNs and GENs to generate the grasp quality, but for the GENs activation function, a sigmoid function was selected instead of ReLU. There were three different experiments to validate the proposed method. The first experiment compared the prediction of GPNs with GraspIt! software on high-quality grasps, the second compared the precision of evaluated grasps of GENs with Graspit! software and the final experiment was an actual test implemented on UR5 and Shadow Hand Lite for object grasping task. The results for the two comparative experiments showed that the proposed method was able to produce the same quality and precision as Graspit!. Meanwhile, in the actual experiment, the robot has performed good grasping of tested objects with 98% success rate. Nevertheless, the authors claimed that their method needs improvement in terms of computational cost and fewer image features.

In another study, Recurrent Neural Network (RNNs) was proposed to control contact force and position of an end effector for constrained flexible manipulators (Tian, Wang & Mao, 2002). In this paper, the RNN approach was used to model the inverse dynamic of the two-DOF flexible robot manipulator. The measured force from the force sensor of the end effector was used to calculate the value of Lagrange multiplier, where the equation of contact force of the end effector with constrained surface was obtained. The RNN approximated the nonlinear parameter of the system and produced a correction factor to compensate the control input from the force controller. The first simulation compared the tracking accuracy of position and force, and the deflection of the flexible link between the proposed work and a PID control. The second was to test the proposed work when undergoing initial position error and physical parameter change consisting of the moment of inertia of the first link and mass of the second joint. From the first simulation, the result showed that the proposed work has better transient response in terms of the steady-state, position and force errors as well as minimal deflection of the flexible link. From the second simulation, the proposed system produced higher position tracking errors while the deflection maintains unchanged. Table 3 shows the summary of the studies on ANN method.

Table 3. Summary of studies on ANN method

Reference	**Method in Details**
Baptista & Sa Da Costa, 2015	NN was introduced to further compensate the force error by modifying the acceleration reference produced by the impedance controller.
Rani & Kumar, 2018	• Torque input control was developed using RBF to approximate the unknown dynamic equation. • An adaptive bound equation is derived to include the reconstructive error from RBF.
Jung & Hsia, 1998	TBNNIC was designed to achieve disturbance rejection for impedance force control at the control input signal while PBNNIC compensates the system's reference trajectory.
Zhao *et al.*, 2020	GPNs was used to predict the grasping point while GENs was used to evaluate the grasping quality.
Tian, Wang & Mao, 2002	The RNN approximated the nonlinear parameter of the system and produced a correction factor to compensate the control input from the force controller.

B. Fuzzy Logic

Fuzzy logic is a controller where it can approximate the output of a system based on the input that are converted into more humanly language. A Fuzzy Inference System (FIS) is a technique of mapping an input space to an output space using fuzzy logic. FIS formalises the reasoning process of human language in terms of fuzzy logic language when deciding on the output according to situations of the inputs. FIS structure generally has four modules, which are fuzzification, knowledge base, inference, and defuzzification (Salleh *et al.,* 2017). It is considered as a rule-based expert system employing linguistic rules that replace complex mathematical representation of system's uncertainties for control. Figure 4 shows the general flowchart for the FLC method.

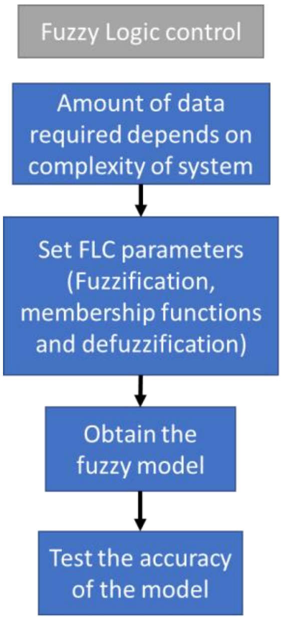

Figure 4. General flowchart for FLC method

A study of two nonlinear fuzzy force controllers, namely Sunderland Fuzzy Adaptive Control (SFAC) and Fuzzy Model Reference Adaptive Control (FMRAC) was proposed (Burn, Short & Bicker, 2003). The advantage of SFAC is on its simple structure which has two rules, and the design is similar to a Proportional Velocity (PV) conventional controller. Meanwhile, FMARC was an improvement from the Model Adaptive Reference Controller (MARC). These methods worked on parameter adjustment based on model error where the fuzzy logic rules were used for the nonlinear adjustment. A contact experimental test was done to observe the control performance of the robot end effector when making contact with various stiffness of cantilevers in the form of rectangular beams made of steel and PVC while applying 30N force. Both controllers were compared to the conventional PV controller on the varied cantilever stiffness. The results showed that FMARC slightly outperformed the other two, although the author claimed that SFAC is preferable due to the simplicity of fuzzy structure.

Fuzzy logic control was also used to achieve stable manipulation by a three-fingered robot hand with two under-actuated fingers (Prado Da Fonseca *et al.*, 2018). The robot hand was mounted with a tactile sensor to provide local tactile information on the grasped object. The force sensor resistor (FSR) supplied the inputs of the force measurement to the fuzzy controller to actuate the joint motor, ensuring stable grasping of the object. The fuzzy memberships were set to triangle functions with four conditions; free, touch, stable and tight. Meanwhile, for the defuzzification phase of motor velocities, there are three triangles and one rectangular memberships which are; low, medium, high, and invert. An experiment on a prototype robotic hand was performed with the application of disturbance by applying external force on the object and rotating the object. The result showed that the fuzzy logic control was able to correct back the grasping force as measured by the FSR to maintain stable grasping.

Another research on grasp-force-adaption control for a three-fingered hand robot with a fuzzy-logic controller for a simulation insertion task was proposed by Doersam, Fatikow & Streit (1994). The grasp-force-adaption was introduced to compensate the reaction force due to the position error while the robot performs the insertion of the peg into a hole. Two fuzzy logic controllers were designed, one as the finger controller which calculates one output for each finger and another is grasp controller that calculates only one output for all fingers. Twelve fuzzy rules were used where the fuzzy controllers' inputs were the normal and tangential forces of the contact-points while the output was the desired force value. Armature current controller DC-motors with friction compensation were used to obtain the position of the fingers. Pythagoras theorem was used to construct a friction cone at the point where the robot fingers exerted the force on the surface, followed by the calculation of the tangential force using the maximal normal force. The simulation on the peg-hole task using both controllers showed that the finger controller gave a better result than the grasp controller in terms of the peg's position and angle due to the independent calculation of forces for each finger by the former.

A slip detection and reflex force estimation were introduced to obtain slip information and grasping force estimation, respectively, to avoid slippage when grasping unknown objects for a 1-DOF prosthetic hand (Deng, Zhang & Duan, 2017). FSR sensors placed on fingertip allowed the prosthetic hand to measure the grasping force which was then applied to the wavelet transformation method to obtain the slippage data. The reflex control used a fuzzy logic control to track the desired force to adjust the initial grasping force when slippage occurs. The input of fuzzy logic was the actual force while the output of the controller was the estimated force, with four triangle membership functions used. An experimental test was done to compare the reflex reaction between the fuzzy logic controller and a PID controller when a disturbance is applied towards the stable grasping hand. The result showed that the fuzzy control was better than the PID controller in terms of the rise time and its capability of following the adjusted desired force when external disturbance occurred.

A study using fuzzy logic control showed the importance of adjusting force control in the robot system consisting of a grinding robot with abrasive belt machine (Xie & Sun, 2016). A pressure sensor was installed to the cylinder driver of the abrasive belt to obtain the force applied when the grinding task was executed. Moreover, an acceleration sensor was mounted on the belt moving rail to calculate the moving belt's velocity. The fuzzy logic controller was applied to reduce the force and position error in the control system. Triangular function was used to design the rules for the five membership of the force data which consists of the rate of change of the force as the input and the control amount of the force as the output. An experiment on three types of zinc alloy faucet work-pieces handles was implemented to observe the grinding task's pass rate with and without the force control. The result showed that the system with the application of force control achieved higher accuracy with a consistent pass rate at about 99.5%. Table 4 shows the summary of the related studies for FLC method.

Table 4. Summary of studies on FLC method

Reference	Method in Detail
Burn, Short & Bicker, 2003	SFAC and FMRAC worked on parameter adjustment based on model error where the fuzzy logic rules were used for the nonlinear adjustment.
Prado Da Fonseca *et al.,* 2018	Fuzzy controller actuated the joint motor to ensure stable grasping of the object according to the applied force.
Doersam, Fatikow & Streit, 1994	The grasp-force-adaption was introduced to compensate the reaction force due to the position error.
Deng, Zhang & Duan, 2017	The reflex control used fuzzy logic to track the desired force to adjust the initial grasping force when slippage occurs.
Xie & Sun, 2016	The controller was used to reduce the force and position errors.

C. Benefits of Intelligent Method

From the discussion above, it can be concluded that intelligent method allows a system to calculate the control input based on a set of control rules to cater the disturbances or uncertainties that occur in the system. The robustness of the system can be improved along with the accuracy of the control due to the ability to adapt and learn. However, due to the number of rules, various types of architecture functions and large amount of input data, the computation can be burdening. This method is suitable to be implemented on a system that uses variety sets of inputs to produce multiple output decision.

IV. RECENT TRENDS OF CONTROL METHOD

A hybrid method is a technique where two or more methods are combined in one system, typically a combination of non-intelligent and intelligent methods. From the discussion above, non-intelligent and intelligent methods have their own capabilities in driving a system to achieve their desired output. This section will discuss some of the researches that have used hybrid method.

A fuzzy NN for three DOF robotic manipulator with two constrained conditions using impedance learning was proposed (He & Dong, 2018). The methods used tan- type Barrier Lyapunov Function (BLF) to handle the unknown state constraints and fuzzy NN to estimate the uncertain dynamic online. Two control strategies that were designed to attain the constrained conditions consist of the control with output constraint and control with full state constraint. The derivation of the model-based control considers the impedance control and fuzzy NN equation. The fuzzy NN inputs were the Cartesian error signals on the x-axis while the output was the approximation of the dynamic parameters. A simulation test to observe the trajectory tracking was done in four conditions, output constraint in free space and constrained space, and full state constraint in free space and constrained space. The results showed that for the free-space conditions, the output constraint and full state constraint have performed good tracking performance. Meanwhile, for constrained space where the robot needs to slide while in contact with a wall, the results showed that both controllers were able to maintain the desired force and track the desired position.

In a study on adaptive Jacobian and Radial Basis Function Neural Network (RBFNN), a method to achieve a precise force control performance by using position/force tracking control for a simulation of two DOF robotic manipulator was proposed (Peng, Yang & Ma, 2019). The robot system consists of two main control loops, namely the inner-loop and outer-loop control. The inner-loop control was designed as an adaptive position tracking controller while the outer-loop was designed to improve the impedance control. Both adaptive Jacobian and RBFNN were implemented within the inner-loop control while PID-like algorithm was used in the outer loop. The adaptive Jacobian method was used to approximate the end effector velocities and interaction torque. Meanwhile, the RBFNN was introduced to compensate the dynamical uncertainties and the uncertain term of adaptive Jacobian. The impedance control was designed to improve the response time and force tracking performance in free or contact space. The proposed method was compared with an Adaptive Force Tracking Impedance Control (AFTIC) (Jung, Hsia & Bonitz, 2001) in a simulation experiment to observe the response time and force overshoot. The results showed that the proposed system has smaller position/force tracking error and reduced the force overshoot with faster response time.

A fuzzy-sliding mode control (FSMC) with a hybrid position/force approach was proposed to a flexible-joint constrained robot (Rafik, 2018). FSMC consists of fuzzy logic and sliding mode control to improve the robustness of the control for the nonlinear system in tracking the desired position. The sliding mode control has the purpose of generating the desired trajectory while the fuzzy logic needs to reduce the sliding mode controller's chattering effect due to the unmodelled noise and uncertainties. The inputs of fuzzy logic were the sliding surface and its derivative while the output was the switching function for the joints' actuation. In addition, a proportional-integral (PI) regulator was used to reduce the response time and static force errors. A simulation test on a Puma 560 model robot was implemented in which it needs to maintain a circular trajectory while maintaining the applied force on a simulated environment. An additional mass was introduced as disturbance to test the robustness of the system. The simulation results showed that the robot followed the desired trajectory while maintaining the desired force. Moreover, the position and motor error tend to converge to zero when the mass was added.

Research by Jhan, Zong-Yu, Lee, Ching-Hung and Lin, (2015) proposed a new adaptive fuzzy neural force controller for a two-DOF robot manipulator model to estimate the unknown robot parameters and manage the tracking control problem. The fuzzy neural system (FNS) is responsible to calculate the nonlinear parameters of the robot dynamic equation for the adaptive control law to produce the required torque for the motors. The structure of the FNS consists of the neural network architecture with a fuzzy logic operation, which has a total of four layers (input layer, output layer, membership layer and rule layer). In order to observe the position and tracking force by the control method, a two-DOF robot manipulator was instructed to move iteratively from one point to another in a simulation test. The result showed that the proposed work tracked the desired trajectory successfully by FNS in free space with the best tracking error performance at iterative number of 110. Meanwhile, for the contact space test, the robot has controlled the force to be equivalent to the 10N desired contact force also at the same iterative number. The author concluded that this method depends on the iterative number to achieve better results.

In another study, an adaptive neural network based on impedance control for tracking force and joint position of a robotic system with uncertain external disturbances was implemented (Yang, Peng & Liu, 2019). The Adaptive Neural Network Force Tracking Impedance Control (ANNFTIC) was developed according to the estimated manipulator's velocity by a nonlinear observer which was derived from the robot's dynamic equation. The impedance control was designed to adapt with two control spaces which are the free space and contact space, where for the contact space the exerted force was applied in one direction only for simplicity. The RBFNN adaptive law was used to estimate the uncertainties with a robust compensation on the external disturbance and approximation errors. Simulation on a two-DOF robot manipulator was done to compare the force and joint position tracking performance between the

AFTIC (Xie & Sun, 2016) and ANNFTIC. In the test, AFTIC was also introduced with the nonlinear observer for fairness comparison. The simulation was done for two conditions which are under fixed force and time-varying force. As for the results, the ANNFTIC showed better position tracking performance in both conditions with smaller force error and faster convergence rate of force tracking. Meanwhile, another simulation test was conducted to compare Neural Network Impedance Control (NNIC) (Li *et al.,* 2013) based on high-gain observer (HGO) (Mosayebi, Ghayour & Sadigh, 2012) with ANNFTIC under model uncertainties and disturbance. The results showed that the proposed work has better position, velocities and force tracking with smaller errors for each parameter. Moreover, it has a faster computing rate than HGO-based NNIC because of fewer NN hidden layers used to estimate the robotic dynamic parameters. Table 5 shows the summary of the studies on hybrid method.

Table 5. Summary of studies on hybrid method

Reference	Method in Details
He & Dong, 2018	Fuzzy NN was developed using impedance control to estimate the uncertain dynamics and contraints of the robot/condition.
Peng, Yang & Ma, 2019	• The adaptive jacobian method was used to approximate the end-effector's velocities and interaction torque. • RBFNN was used to compensate the dynamical uncertainties and the uncertain term of adaptive jacobian.
Rafik, 2018	• The sliding mode control generates the desired trajectory • Fuzzy logic reduces the sliding mode controller's chattering effect due to the unmodelled noise and uncertainties.
Jhan, Zong-Yu; Lee, Ching-Hung;Lin, 2015	FNS was used to calculate the nonlinear parameters of the robot's dynamic equation for the adaptive control law.
Yang, Peng & Liu, 2019	• Developed the ANNFTIC from the estimated manipulator's velocity. • The RBFNN adaptive law estimates the uncertainties of the external disturbance and approximation errors.

V. CONCLUSION

It can be concluded that both non-intelligent and intelligent methods allow a system to calculate the control input based on their control laws which use either the error or the measured data of the joint variables. Non-intelligent methods allow a system to update the selected control parameter with faster computation time when external disturbance or uncertainties occur. This is due to the fixed control law that does not require the application of massive data calculation of the input to calculate the desired control input. However, these methods could not adapt with the conditions beyond some level of robustness in which modification of the control law is necessary. This is no easy to do since the complicated rules are based on complex mathematical equations of the robot dynamic. On the other hand, the flexibility of intelligent method design is based on the selection of different learning algorithms which can suit different problems. Furthermore, intelligent methods have the capability to update the control parameters and predict the desired output through the learning process but with slower computation time caused by the massive data used. Besides, intelligent controller is comparatively easier to be developed than non-intelligent controller as long as large amount of quality data can be provided. Therefore, recent studies suggest hybrid method which combines both of the above methods to improve the robustness and the accuracy of the control system while improving the computational time. It occupies the advantages of each method to produce an optimal force control method. This conclusion was based on the author's reading and opinion. Due to the breadth of the field, this paper discusses only several intelligent and non-intelligent control methods for robotic applications. Many other approaches can be found within this field because of the tremendous interest related to robotic force control.

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