A Review of SCARA Robot Control System

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***Abstract*—In the era of industrial revolution 4.0 (IR4.0), robotics is a common automation tool to comply the repetitive and dangerous jobs for assisting the human workforce. Among the robotic arm, the SCARA robot is one of the well-established robots in the industry due to its high speed and high accuracy. To achieve good control at high speed, the controller is key to ensuring the SCARA robot at such a performance. This paper presents a brief review of the controllers and their pros and cons when applying to the SCARA robot. The reviewed controllers include PID Control, fuzzy logic control, neural networks control, sliding mode control, impedance control, adaptive control and robust control. Besides that, the review also covers the implementation of the Internet of Things (IoT) and artificial intelligence (AI) on the SCARA robot as the trend of IR 4.0.**

Keywords—robotic, SCARA robot, controller, Internet of Things

I. Introduction

In the 20th century, robotics has become more important as a flexible automation tool to comply the repetitive and dangerous jobs for reducing worker hazards and tiredness. At the same time, the use of robot automation also increases production efficiency and consistency. The first implementation of robots started in 1937, which is a cartesian robot [1]. Since that, the cartesian robot is widely been used in the automation industry such as in agriculture, automated storage and retrieval system (AS/RS) and marble mosaic tiling automation [2]–[4]. However, the operation range and the precision of the cartesian robot are poorer than other types of robots [5]. As a result of the continued improvement of researchers, the first cylindrical robot was introduced and installed in the United States in 1962, [6].

Cylindrical robots are normally applied in the assembling industries such as welding and dealing with die-casting equipment [7]. The cylindrical robot has better accuracy compared to the cartesian robot, but the range of motion is limited to a cylindrical shape. Therefore, the spherical robot and articulated robot are implemented to improve the range of motion [8]. Due to the improvement made, the spherical robot and articulated robot are widely been used for applications that required higher reachability, such as applications in the military field, medical, material handling and manufacturing [9]–[11].

Last but not least is the Selective Compliance Articulated Robot Arm (SCARA) robot which will be mainly discussed in this review paper. SCARA robot has high precision and accuracy at the same time power efficiency as there is only 1 joint which is joint 3 need to operate against gravity force. Therefore, the SCARA robot is a good choice for an industry that requires high precision and low power consumption. To achieve high accuracy, the SCARA robot requires an advanced controller to handle and control the nonlinear dynamic behaviour of the robot system [12], [13]. The detail of the SCARA robot will be discussed in the next section including the implementation, kinematic modelling, dynamic modelling and trajectory planning.

II. SCARA Robot

SCARA robot was invented in 1979 by a Japanese professor, Professor Hiroshi Makino [1]. The SCARA robot development intends to enhance the robot performance with high accuracy and fast operation, both of which are SCARA's benefits [14]. Therefore, the establishment of the SCARA robot had been implemented in many industries such as the medical industry and manufacturing industry [15].

A. Kinematic Modelling

Kinematic modelling for the SCARA robot provides the physical description in the form of mathematics of the robot. The kinematic modelling can be divided into two parts which are forward kinematic modelling and inverse kinematic modelling. The forward kinematic modelling for the SCARA is formulated to yield the end-effector position with the joint angles as input. Therefore, the forward kinematic modelling can apply to produce a position planning for the SCARA robot. By inverting the kinematic model, the desired end-effector position can be used in inverse kinematic modelling to yield the desired joint angles [16]. Therefore, kinematic modelling is essential to provide the working envelope and match the function of the robot arm to its application [17]. The position of the robot arm is described via the widely used Denavit-Hartenherg approach, which uses the homogeneous transformation matrix to formulate the robot's kinematics. [17]. The joint link homogeneous transformation matrix is formulated as shown in (1).

$$H_n^{n-1} = \begin{bmatrix} \cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\,\sin\alpha_n & r_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\theta_n & r_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where n is the destination joint, α_n, θ_n, d_n and r_n are the Denavit-Hartenberg parameters. The α_n is the angle formed by orthogonal projections of joint axes Z_n and Z_{n+1} onto a plane perpendicular to the same normal, $\theta_n$is the angle formed by the orthogonal projections of the common normal, X_n and X_{n+1}, onto a plane perpendicular to the joint axes Z, d_n is the distance between X_n and X_{n+1} along with Z_n and r_n is the distance between the common normals to axes Z_n and Z_{n+1} along with X_{n+1}. The Denavit-Hartenberg parameter can be obtained from the joint link parameter of the robotic arm. As shown in (2), multiplying the homogeneous transformation matrix for each joint will get the final position and the rotation angle for the robotic arm.

$$H_n^0 = H_1^0 H_2^1 H_3^2 \dots H_n^{n-1} \quad (2)$$

B. Dynamic Modelling

The purpose of dynamic modelling is to predict the force and torque behaviour of the robot system with various payloads conditions [18]. From the dynamic modelling, the required torque, joint velocity, joint acceleration and joint position of the SCARA robot can be calculated and used as a reference to select a suitable actuator and transmission system [14],[19]. To design control systems, it is possible to apply the mathematical dynamic model of the SCARA robot arm's dynamic behaviour. The best controller matching the required performance can then be selected for realization. The Newton-Euler equation and the Lagrangian equation are typically employed as the two methodologies for dynamic modelling of the SCARA robot. The general equation of the Lagrange equation and the Newton-Euler equation are shown in (3) and (4) respectively.

$$\tau = \frac{d}{dt}\left(\frac{\partial T}{\partial \ddot{q}}\right) - \frac{\partial T}{\partial q} + \frac{\partial U}{\partial q} \quad (3)$$

$$\tau = M(q)\ddot{q} + C(q,\ddot{q})\dot{q} + G(q) \quad (4)$$

where τ is the torque for each joint, q is the joint displacement, $\dot{q}$ is the joint velocity, $\ddot{q}$ is the joint acceleration, Tis the kinematic energy and U is the potential energy. Both of the methods can estimate the dynamic behaviour of the SCARA robot well.

C. Trajectory planning

Trajectory planning is one of the procedures to design a robot movement by defining the desired path, acceleration and velocity of the robot arm [20]. The information computed from the trajectory planning is fed into the dynamic model to obtain the desired torque in a time sequence manner which can then be used in performing the path movement by the controller [21]. The controller ability and stability can be studied by the achievement of the robot arm position compare to the desired position at each time sequence point in the trajectory [22]. To achieve trajectory planning the joint space method and the cartesian space method can be used [23]. The joint space method is applying Third-order Polynomial to compute the desired path, acceleration and velocity of the robotic arm as the general formula of the third-order polynomial is shown in (5).

$$\theta(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 \quad (5)$$

where θ is the joint position for the robot arm, C_i $(i = 0\ to\ 3)$ are the unknown constants, and t is the time. When the initial and final conditions of the robotic arm had been decided for the robotic arm to move from the initial position to the final position through a defined path, the parameters will be used to compute the acceleration and velocity of the robotic arm at each point and period on the desired path. Using the defined acceleration and velocity at each point and period on the desired path, the controller will control the robot arm to achieve the requirement of each point on the desired path. The accuracy of the robot arm to perform the desired path lies in the controller. Thus, the controller design is a very important element in defining the performance of the SCARA robot.

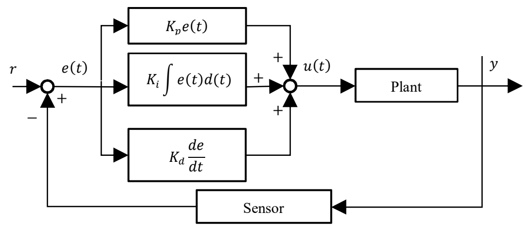

Fig. 1. General block diagram for PID controller.

III. SCARA Robot Control System

The SCARA robot's controller is used to govern the robot to perform desired tasks. Different applications require different ranges of allowable end-effector error compared to the desired position. The error of the robot is a performance indicator in the robot arm design. Besides the accuracy of the robot, the speed of the robot is also a performance concern, as it defines the amount of time required to complete the desired task. As known that the SCARA robot has high precision and operation speed, thus, the controller for the SCARA is required to handle the high operation speed and high accuracy computation. Moreover, the SCARA robot consists of a nonlinear dynamic system due to friction and uncertain payload. Thus, the design and development of the controller for the SCARA robot is not an easy task. As a preliminary effort to design and develop the controller, the review is conducted on various types of controller systems used for controlling the SCARA robot. The controllers are such as PID control, robust control, neural networks control, fuzzy logic control, adaptive control and sliding mode control. The advantages and disadvantages of each of these control systems for the SCARA robot are discussed and compared.

A. PID Control

PID control is a closed-loop control system as shown in Fig 1. The PID control signal can be formulated as the following (6).

$$u(t) = K_p e(t) + K_i \int e(t)d(t) + K_d \frac{de}{dt} \quad (6)$$

where $u(t)$ is the control signal, $e(t)$ is the error signal, r is the desired output, K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain. Each of the gains is crucial as the parameters will affect the transient response of the output and the output will be feedback to the system to compare with the reference signal to yield the control signal. As the PID controller is simple, PID controller is widely been used in many fields including robots application [24], [25]. However, the PID control only has good stability in a system that behaves linearly or near to linear [26]. Therefore, in most cases, the performance of PID Control is not sufficient when the system behaves non-linearly [27], [28]. Besides that, the PID controller also has insufficient sensitivity to counter the high speed and high precision operation requirements [29]. To overcome the linear response of the PID controller many

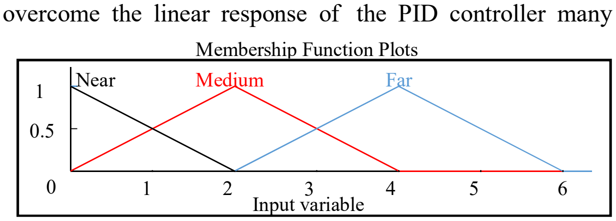

Fig. 2. The example of the membership function in graph form.

approaches had been adopted to actively change the PID gain based on the operating condition. The commentary adopted method is by using fuzzy logic and AI algorithms to improve the performance of the PID control.

B. Fuzzy Logic Control

Based on the digital operation of 1 and 0, the Fuzzy Logic Control is derived from mathematical logic to compute the signal between 1 and 0. The signal between 1 and 0 can be obtained from the input variable according to the membership function which was assigned as shown in Fig 2 and this process is called the inference engine [25]. As shown in Fig 2, the fuzzy logic will compute the signal according to the slope of the membership function. The computed signal will be used for controlling the robotic arm according to the output membership function as shown in Fig 3.

The PID controller gain is actively tuned according to the weightage score computed from the inference engine. These overcome the fixed gain that requires pre-tuning and lack of adaptability to the nonlinear behaviour of the SCARA robot [30]. Overcoming the limitation of the PID controller using the Fuzzy Logic improved the smoothness and stability of the robot as reported by Oktarina and colleagues 2019. Furthermore, the implementation of fuzzy logic is simple and thus it is widely used [25].

C. Sliding Mode Control

The Sliding Mode Control is a nonlinear dynamic control system [13]. The operating concept of the Sliding Mode Control is to control the system state variables toward a designated surface known as the sliding surface and ensure the state variable trajectory is on this designated surface. Equation (7) is a sliding mode surface that is commonly been used to design a Sliding Mode Controller.

$$s = (\frac{d}{dt} + \lambda)^{m-1} X \qquad (7)$$

where X is the system state error, s is the sliding surface, λ is the positive constant and m is the system order. As the system state gets closer to the sliding surface, s equals zero, and X asymptotically reaches zero. Besides the high accuracy, the Sliding Mode Control can also handle parametric uncertainties and also external disturbances [31]. With that, Sliding Mode Control is capable of managing the SCARA robot's nonlinear dynamic system. However, the disadvantage of the Sliding Mode Control is it can cause high-frequency oscillation in the control signal in a discontinuous control system [32]. The high-frequency oscillation can lead to system instability.

D. Adaptive Control

Adaptive Control is also one of the advanced controllers which can handle nonlinear dynamics systems. The adaptive controller generally contains four blocks, which are the plant,

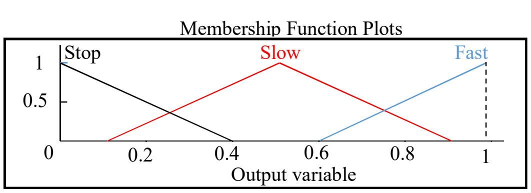

Fig. 3. The example of the output membership function in the graph form.

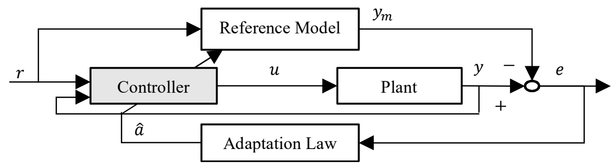

Fig. 4. Adaptive Control System.

reference model, control law and adaptation mechanism as shown in Fig 4. The components in the adaptive control system are designed according to the plant. Considering the plant for the SCARA robot is a continuous-time linear time-invariant plant as a reference model, the reference model can be modelled using the general state-space model as per (8) and (9).

$$\dot{x}(t) = Ax(t) + B_1 w(t) + B_2 u(t) \qquad (8)$$

$$y(t) = C_2 x(t) + D_{12} w(t) \qquad (9)$$

where $\dot{x}(t)$ is the state of the plant, $w(t)$ is the disturbance input, $y(t)$ is the final output and A, B_1, B_2, C_2, D_{12} is the constant matrixes. The adaptation mechanism which is the adaption control law will continuously be adjusting the adjustable parameter in the controller according to the operating environment based on the reference model [33]. The adaptation control law can be formulated as shown in (10) where $x_m(t)$ is the reference output, $r(t)$ is the step-type reference signal, $x_c(t)$ is the integral compensator and $K(t)$, $F(t)$, $H(t)$ will be updated using (11).

$$u(t) = [K(t) \quad F(t) \quad H(t)] \begin{bmatrix} y(t) \\ x_m(t) \\ r(t) \end{bmatrix} + Gx_c(t) \qquad (10)$$

$$[\dot{K}(t) \quad \dot{F}(t) \quad \dot{H}(t)] = e(t)[y(t)^T \, x_m(t)^T \, r(t)^T \,]\Phi \qquad (11)$$

where $e(t)$ is the tracking error, Φ and G can be assigned based on the behaviour of the SCARA robot. Therefore, Adaptive Control can perform well with unknown parameters as the controller can adapt to the unknown parameters [34]. As the uncertainty of the environment can be predicted by the controller, the performance of the controller in terms of accuracy is much better than the fixed gain controller such as the PID controller, especially with unknown parameters. The ability to self-adapt to the unknown environment of the adaptive controller can guarantee the stability and convergence of the controller [35].

E. Robust Control

Robust Control is a type of controller designed to enhance the performance of the controller in a certain range. The Robust controller idea is proposed by Evan Anderson and Paul Dupuis [36]. Consider using the same plant in (7) and (8) which is the linear time-invariant plant. The equation for the system can be derived as (12) and (13).

$$\dot{x} = Ax + Bu \qquad (12)$$

$$y = Cs + Du \qquad (13)$$

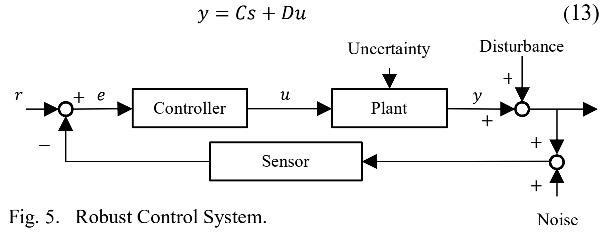

Fig. 5. Robust Control System.

TABLE I. SUMMARY OF PROS AND CONS OF THE CONTROL METHOD FOR THE SCARA ROBOT.

Control Methods	Characteristics	Ref
PID Control	Stable control. Easy to apply. Insufficient for the non-linear control system. Low precision. Unable to adapt to different operating conditions.	[24] [25] [27] [28] [29]
Fuzzy Logic Control	Stable control Easy to apply. High accuracy. Able to adapt to different operating conditions.	[25] [30]
Sliding Mode Control	Able to handle uncertain parameters. Able to handle external disturbance. High precision. Cause high-frequency oscillation in the control signal	[31] [32] [39]
Adaptive Control	Able to handle uncertain situations. High accuracy and precision.	[33] [34] [35]
Robust Control	Able to handle uncertain situations in a certain range. High accuracy and precision in a certain range.	[37] [38]

where A, B, C and D are the constant matrix that will be defined during the control system development. The idea of a Robust control system is to design a control system which is included uncertainty criteria which are noise and disturbance as shown in Fig 5. When the uncertainty criteria are included in the control system as shown in Fig 5, the control system is operating as in the real situation which contains uncertainty input. Therefore, the Robust Control can improve the position error of the robotic arm when compared with PID Controller [37]. Thus, Robust Control can be implemented in a situation that consists of uncertainty parameters [38].

A summary of the control system reviewed is tabulated in Table 1.

IV. SCARA Robot with AI Control and IoT

Nowadays, the technology of the processor consists of powerful computing speeds that give rise to AI technology. By applying the AI technology to a SCARA robot controller, the AI can optimise the control parameter and adapt to uncertain parameters for the SCARA robot such as particle swarm optimization (PSO), genetic algorithm (GA) and neural network. Therefore, the implementation of AI technology can improve the performance of the SCARA robot. Besides AI technology, the IoT is also a technology that can apply to the SCARA robot.

A. *AI Control*

- Neural Network Control

Neural networks is widely been used in the industry to overcome the various type of operating environments. Neural Network is comprised of node layers with the input layer, output layer and hidden layers as shown in Fig 6. Every node has associated the weight and threshold for training the algorithm. In the process of training, the output will be fine-tuned in every iteration until it is achieving desired error value. Therefore, the Neural Network consumes time and data set to train the algorithm to achieve desired performance. The well-trained Neural Network which is known as the mature algorithm can achieve better precise control compared to PID Controller [19]. The mature algorithm used estimation of position and motion error to actively tune the PID gain in dealing with the non-linear behaviour of the SCARA robot dynamic [29].

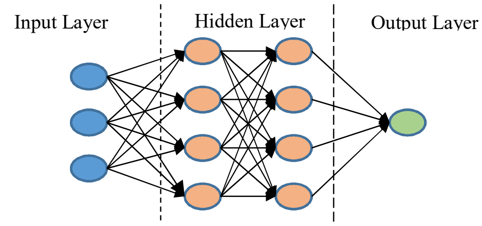

Fig. 6. Artificial Neural Network.

- Particle Swarm Optimization

PSO algorithm is a type of AI that can compute the optimal solution for a control system. PSO algorithm uses particles to compute the best solution in a dimension space. The particles will move randomly in the dimension space to search for the best solution within the range. Every particle will be kept updated in its position and velocity by using (14) and (15).

$$v_{id}(t+1) = \omega v_{id}(t) + U_1\emptyset_1[P_{id}(t) - L_{id}(t)] + U_2\emptyset_2[P_{\delta d}(t) - L_{id}(t)] \quad (14)$$

$$L_{id}(t+1) = L_{id}(t) + v_{id}(t+1) \quad (15)$$

where v is the particle velocity, L is the particle's position, ω is the inertial weight factor which will be defined according to the design, U is the constant multiplier called swarm confidence, $\emptyset$ is random that is uniformly distributed, P is the previous particles point that consists of the best fitness value and δ is the index of the best particles and d is the dimension space. The position and velocity of the particles will update every iteration and most of the particles will converge to a small region. The fittest vector will be selected as it will be the optimal solution for the system. Therefore, the PSO algorithm can apply to a traditional control system such as PID to define the optimal gain value for the SCARA robot control system [40]–[42]. Moreover, the PSO algorithm consists of some advantages which are good computational efficiency, stable convergence characteristics and ease of implementation [41]. There are also different AI algorithms that can compute the optimal solution for the control system.

- Genetic Algorithm

GA is another algorithm that can compute the optimal solution for the system. However, the difference between PSO and GA is the implementation of GA is normally applied with fuzzy logic control because the GA is efficient and easy to apply for multivariable optimisation problems [50]. The flowchart which consists of GA elements is shown in Fig 7.

Each of the elements plays an important role to ensure the GA is mature to optimise the fuzzy logic control. At the beginning of the GA, the string of parameters are the genes in a chromosome which will be defined according to the optimization problem. Next is the initial generation which will form the initial generation with the random number. The initial generation will be evaluated by using the fitness function as a performance index to verify the optimal solution. After the performance

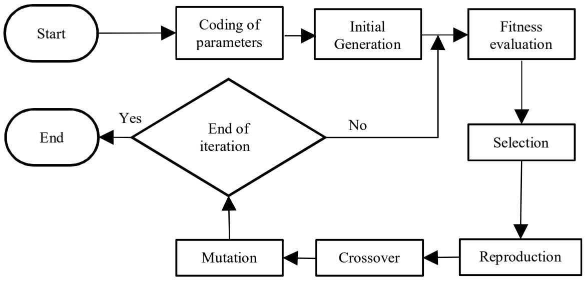

Fig. 7. Flowchart for Genetic algorithm.

index had been computed, the chromosome which has a better performance index will be selected for the next step which is reproduction.

The next generation will be formed from the mating pool. The new generation will have a high similarity with the old generation which has a high-performance index. The new generation will randomly select a few pairs of strings to exchange the chromosome and this process is called crossover. However, to avoid trapping in the local minimum, the mutation is required to randomly change the chromosome. The loop will be ongoing until it reaches the number of iterations or the GA is mature. A matured GA can improve fuzzy logic control by computing the optimal membership functions and fuzzy rules [43].

A summary of the control system reviewed is tabulated in TABLE II.

B. IoT

As mentioned above, the purpose of advanced control and AI control is to enhance the control system to assure the SCARA robot's accuracy and stability. On another hand, the IoT play another role which is connecting the SCARA robot with other devices such as computer and cloud server as the IoT is a global network for the machine to interact between other machines and devices [44].

The IoT consists of three elements which are hardware, middleware and presentation [45]. Hardware is the sensor, actuator and communication hardware such as the SCARA robot, middleware is the cloud storage and computing tools such as the cloud server and computer and the presentation is the tools that can be widely accessed on other platforms such as the smartphone or laptop [44], [45]. Therefore, the technology of IoT can be implemented in many applications such as health care, transport systems, industrial plants, robotics and the military [46]. By applying the IoT, the robot can connect to a computer to improve its computation ability [47]. As the computation can run on an independent computer, the SCARA robot does not consume energy for the computation process which can decrease the energy consumption when the SCARA robot is mounted on a mobile robot [47]. The mobile robot only focuses on the communication system to receive the control signal from the cloud [47]. Furthermore, the technology of IoT can improve the performance and calibrate the SCARA robot easily by just replacing an advanced control or an AI control with a computer that is linked with the SCARA robot [48]. Moreover, the IoT also allows the user to remote control the SCARA robot by just using a computer or even a smartphone [48].

TABLE II. SUMMARY OF PROS AND CONS OF THE AI CONTROL FOR THE SCARA ROBOT.

Control Methods	Characteristics	Ref
Neural Network Control	High accuracy and precision. Gentle control behaviour. Able to adapt to different operating conditions. Required data and time to train the algorithm.	[20] [32]
Particle Swarm Optimization	Optimise the PID controller. Good computational efficiency. Stable converge characteristics. Easy to implement.	[47] [48] [49]
Genetic Algorithm	Optimise the fuzzy logic control. Easy to implement. Efficient for multivariable optimisation.	[43] [50]

However, there are some challenges to the implementation of the IoT. The main challenge is security and privacy [49]. As the IoT may involve access to personal data that could implicate the personal privacy of the user. Moreover, the challenge of the IoT is the platform, programming language and protocol are different between different companies [59]. This will cause difficulty in connecting different types of devices from other companies [49].

Last but not least is the cellular data which is the core of IoT as the cellular data commonly used is the 4G which is not optimised for IoT implementation [50]. Therefore, the wide implementation of IoT lies in the solution to the above challenges.

V. Conclusion and Future Trend

In conclusion, the controller is crucial for a SCARA robot as a driver to move the robotic arm. There are many different controller types, though, that can be used with the SCARA robot. The controller selection needs to match the application of the robot as the controller has its pros and cons. Selection of controller according to the SCARA robot application can also prevent overdesign for the robot as the overdesign is a waste of resources. If the application involves linear behaviour, the PID control and fuzzy control is the right choice. As both control systems have fixed gain control systems. Thus, the PID control and fuzzy logic control is suitable for fixed load robot which did not have much uncertainty. On the other hand, advanced control like the sliding mode control, adaptive control and robust control are suitable to handle high uncertainty situations. Therefore, the advanced control system is more suitable to be applied to the SCARA robot due to the SCARA robot uncertainty parameters.

In the future, the technology of AI can assist the advanced controller to achieve better performance for the SCARA robot. However, such powerful AI needed a very powerful computation computer. Therefore, IoT technology can link the SCARA robot with a powerful computation computer such as a supercomputer. Furthermore, the IoT can create a more user-friendly environment for the user as IoT can allow the user to control the SCARA robot by just using a smartphone.

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