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Exploring Industrial Robot Control Systems: Components, Software and Applications

[1]Mary Robinson and [2]Gerry Adams
[1, 2] College of Science and Engineering, University of Galway, Galway, Ireland
[2]gadams@universityofgalway.ie

Correspondence should be addressed to Gerry Adams: gadams@universityofgalway.ie

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Abstract – Automated manufacturing facilities are governed by resilient control systems that need little or negligible human interaction. Broadly speaking, an industrial controller is responsible for transmitting instructions to machinery in order to carry out a designated operation, while also receiving feedback data that enables it to oversee and ascertain the accurate implementation of those instructions. This article examines the several elements and software systems included in the control of industrial robots. This paper examines the significance of sensors, axis controllers, and actuators in attaining accurate control over industrial robots. The use of industrial Ethernet technology is emphasized as a viable approach to mitigate the issues associated with excessive wiring and interference. The essay also highlights the need of offline programming tools and impedance control in order to enhance programming efficiency and facilitate natural contact with robots. Furthermore, this paper examines the difficulties and progress made in the realm of robot control specifically in relation to tasks such as bin picking, assembly, and machining.

Keywords – Automated Manufacturing, Industrial Robot Control System, Robot Control Development, Point-To-Point Control, Automatic Control.

I. INTRODUCTION

The historical relationship between robotics and control theory spans more than 50 years, showcasing a significant interaction between the two fields. Boubaker [1] conducted a comprehensive analysis of the historical context of the interaction between control theory and robotics. Their examination primarily focused on the foundational aspects, specifically highlighting how control theory has facilitated the resolution of basic challenges in the field of robotics. Additionally, they explored how the exigencies encountered in robotics have spurred the advancement of novel control theory methodologies. The primary emphasis of Bondi, Casalino, and Gambardella [2] was on the first stages, since the significance of novel findings often requires a substantial amount of time to be comprehensively recognized and to have influence on real-world implementations. The field of robotics has had significant advancements in recent years, particularly during the last decade or two, and prospects for further progress remain promising. During its early stages, the field of robotics was primarily influenced and controlled by the machine tool industry. Consequently, the first approach in the development of robotics was designing mechanisms with high rigidity, whereby each axis (joint) was controlled autonomously as a single-input/single-output (SISO) linear system.

The use of point-to-point control has facilitated the execution of basic operations, such as the transfer of materials and the process of spot welding. The use of continuous-path tracking has facilitated the execution of more intricate operations, such as arc welding and spray painting. The perception of the surrounding world was either restricted or absent. The examination of increasingly complex jobs, such as the assembly process, necessitates the implementation of regulations pertaining to contact pressures and times. The need for enhanced comprehension of the intricate and interrelated nonlinear dynamics of robotics arose due to the need for increasing operational speed and improved payload-to-weight ratios. The need for this particular condition served as a driving force behind the advancement of novel theoretical findings in the domains of nonlinear, robust, and adaptive control. Consequently, these advancements facilitated the implementation of increasingly intricate applications. Currently, robot control systems have reached a high level of sophistication, including integrated force and vision systems. Mobile robots, underwater and aerial robots, robot networks, surgical robots, and several other types of robots are assuming more prominent roles within society. Robots are often used as instructional instruments in K-12 and introductory college classes.

According to Candelas et al. [3], like the concept of "automatic control," the topic of robot control has several interpretations about its bounds. The technology used in the servo loops that regulate the robot joints may be understood as the most constrained interpretation of robot control. In the field of robotics, the term "robot control" often refers to the technological aspects involved in governing the electromechanical systems of a robot. This study will focus on an expanded concept that encompasses not just joint control, but also incorporates modeling, identification, design, trajectory planning, and learning. The development of Industrial Robots has mostly been influenced by the automobile industries and associated supply networks, which have emerged as dominant customers of industrial robots. The current situation has necessitated that producers of robots prioritize their research and development efforts on achieving machines that exhibit exceptional cost effectiveness, reliability, and productivity.

The acquisition of these fundamental prerequisites has rendered robot control a pivotal technological advancement. Similar to several other goods, the use of model-based control has resulted in a significant improvement in performance for industrial robots [4]. ABB Robotics was the pioneering robot manufacturer to use model-based robot control. The majority of the information presented in this study draws from the insights gained from the development of robot control systems at ABB Robotics. In the forthcoming years, the influence of the automotive sector on the advancement of robotics is anticipated to diminish. Presently, the market for robots used in press tending, vehicle body assembly, painting, and coating is already saturated. Consequently, makers of robots have intensified their endeavors in developing alternative applications and expanding their client base. The straight application of robot solutions created for the automobile sector is sometimes challenging, necessitating additional refinement of robot control mechanisms.

The advent of industrial automation has necessitated the development of increasingly sophisticated robot control systems in order to effectively address the heightened requirements. The objective of this article is to provide a comprehensive examination of the constituent elements and software systems included in the management of industrial robots, while also emphasizing the progress and obstacles encountered within this domain. This publication functions as a great resource for those engaged in research, engineering, and manufacturing who possess an interest in comprehending the most recent advancements in the field of industrial robot control. The rest of the article has been organized as follows: Section II review the concepts of Industrial Robot Control (IRC) system, its components, programme selection, and the evaluation of control means. Section III presents a discussion of performance/cost-driven robot control development. Section IV focusses on robot control development driven by automation technologies. Section V reviews the application-driven robot control development concept. Lastly, in Section VI, a conclusion to the research is drawn.

II. INDUSTRIAL ROBOT CONTROL SYSTEM

Component of IRC System

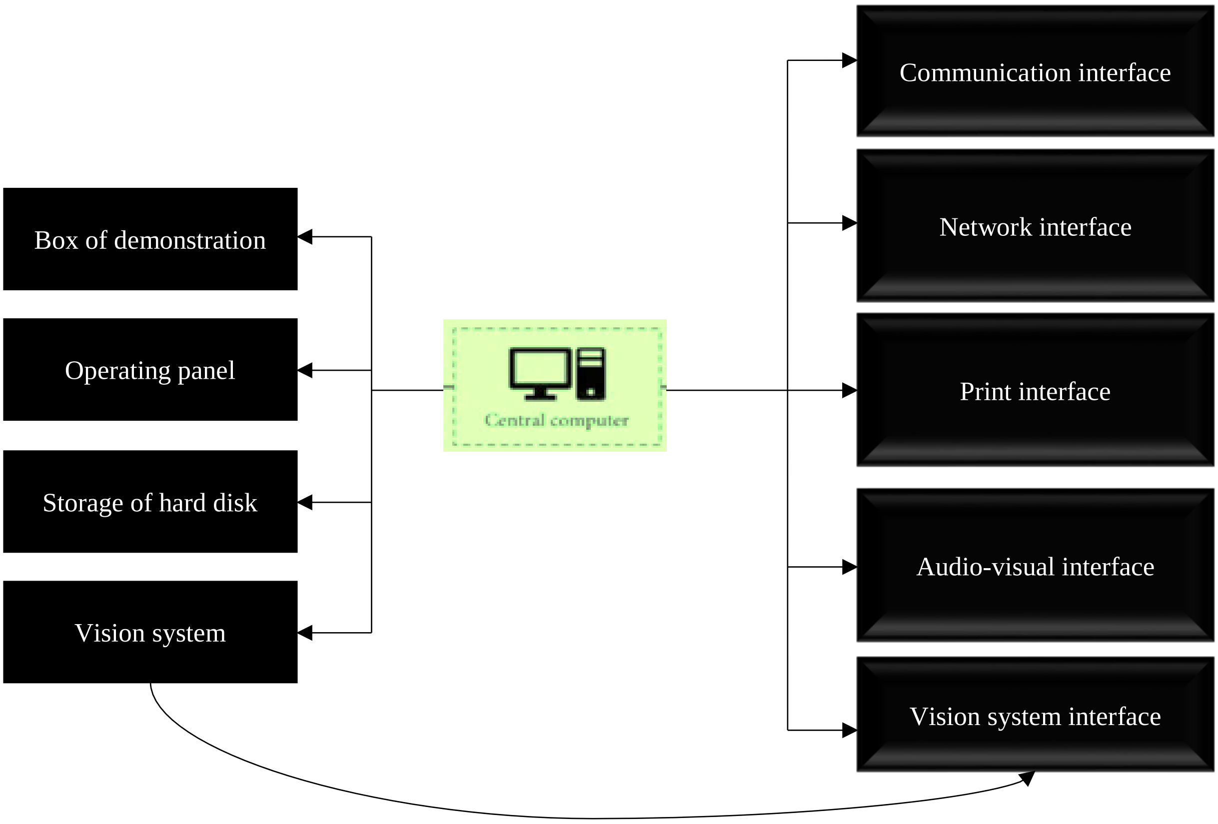

Fig 1. Robot Control Model Component.

Industrial Robot Control (IRC) system, is composed of factors like demonstration box, auxiliary equipment, connection terminals, sensors, an axis controller, and a computer [5]. The robot control system's control computer is made of microcomputers and microprocessors. Its primary function is to serve as a central command unit, overseeing various aspects of control. An enclosed storage unit and a central processing unit (CPU) are integrated into the demonstration case. The primary purpose of the program is to establish a set of parameters and illustrate their effects via the use of human-computer interaction. The primary uses of sensors in industrial robotics include tactile, visual, and force sensing. These sensors serve the purpose of detecting various types of information and facilitating control over the robotic system. Axis controllers are very valuable components that are used for the purpose of regulating the velocity of a robot, as well as managing various operational sequences. The diverse auxiliary devices are primarily used in combination with firm robots and serve as significant auxiliary components, as seen in **Fig 1**.

Programme Selection of IRC System

The automation of contemporary industries has led to the expansion and complexity of robot production lines. As a result, these production lines now include a greater number of robots, hence necessitating more advanced robot control systems to meet the increased demands. **Fig 2** illustrates a prevalent strategy for robot automation in contemporary times. Within this framework, the personal computer (PC) is unable to do algorithmic processing. Instead, it functions as a conduit between humans and machines, while the responsibility of intricate arithmetic processing lies with the motion controller. The real-time influence of the PC may be mitigated throughout the software development process for the host computer. Hence, the real-time demands imposed on the PC are minimal.

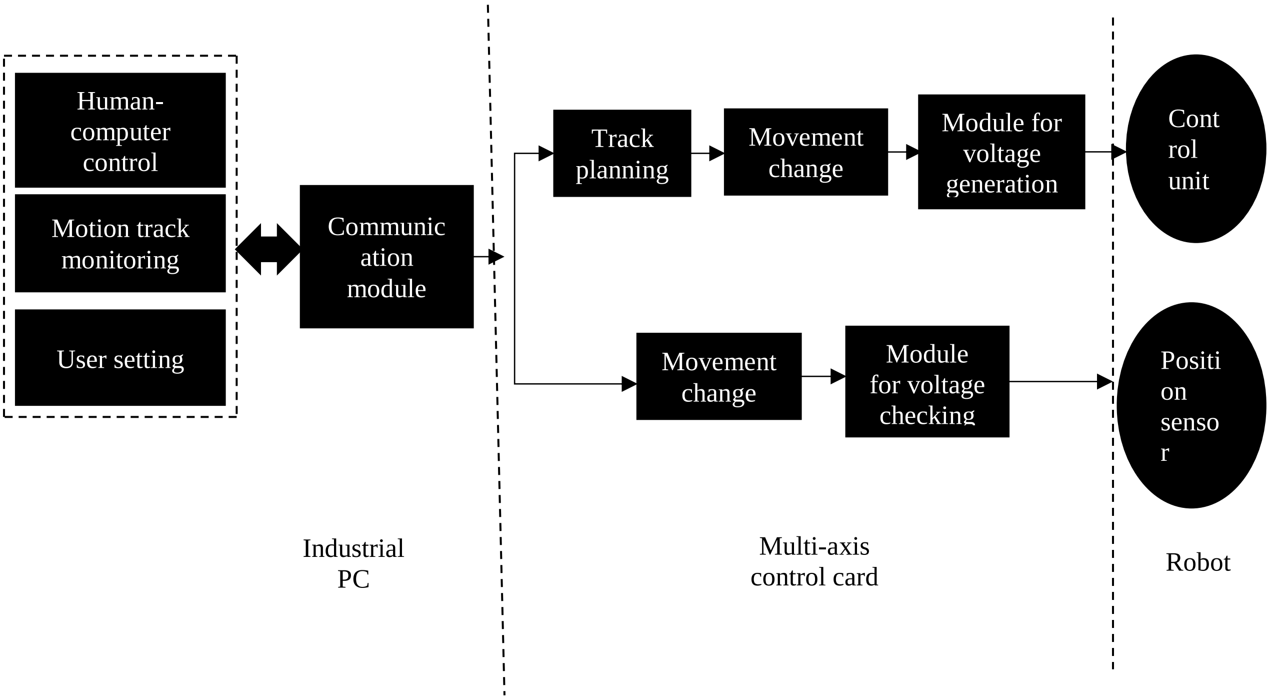

Fig 2. Framework for Robot Automation Management.

Consequently, despite the augmented strain on the motion controller, the use of a high-performance processor like the digital signal processor (DSP) is sufficient to fulfill the requirements. Simultaneously, the integration of industrial Ethernet technology offers a viable solution to the challenges posed by the excessive number of wires and significant interference resulting from the conventional linkage of motion control cards to personal computers via PCI connections. Additionally, the structural concept of the design for industrial robot automation is shown in **Fig 3**. The personal computer (PC), which functions as the principal platform for enabling human-machine interaction, is a traditional computing device powered by the Windows operating system. A network cable is utilized to connect the motion control card, which is outfitted with an EtherCAT, to the personal computer. It executes control algorithms and interpolation operations based on the instructions provided by the PC.

Evaluation of Control Means for IRC System

Actuators are used within the context of industrial robotics to selectively regulate certain locations. This kind of control enables the use of the robot without necessitating various specifications to achieve the respective goal locations. Precise and reliable movement is necessary for robot`s unilateral control location at neighboring sites. Torque control is most often used in the context of using robust robots to manipulate various objects; this kind of manipulation calls for controlling positional coordinates and applying the best torque for certain tasks. Industrial robots must be able to understand basic changes in their surroundings and make good use of sensors. By drawing on its knowledge base, the robot is able to improve its self-learning and adaptive abilities.

Industrial robots rely heavily on actuators to control their speed, trajectory, and position precision. Industrial robots must take into account a number of factors to ensure that its motion is accurate and orderly, stable across tasks, controlled at a steady pace, and has a smoother trajectory. The software system described here has two parts: one for the lower-level computer, called a slave, and one for the higher-level computer, called a master. An operating system specifically tailored to run on personal computers is the master entity. The configuration of the Field-Programmable Gate Array (FPGA) [6] and the Digital Signal Processor (DSP) [7] are executed through the Code Composer Studio (CCS) [8]. The development of the subordinate software entails the configuration of the FPGA and DSP, which are manufactured utilizing the Quartus and CCS software packages, respectively. **Fig 4** depicts the software model of the control system.

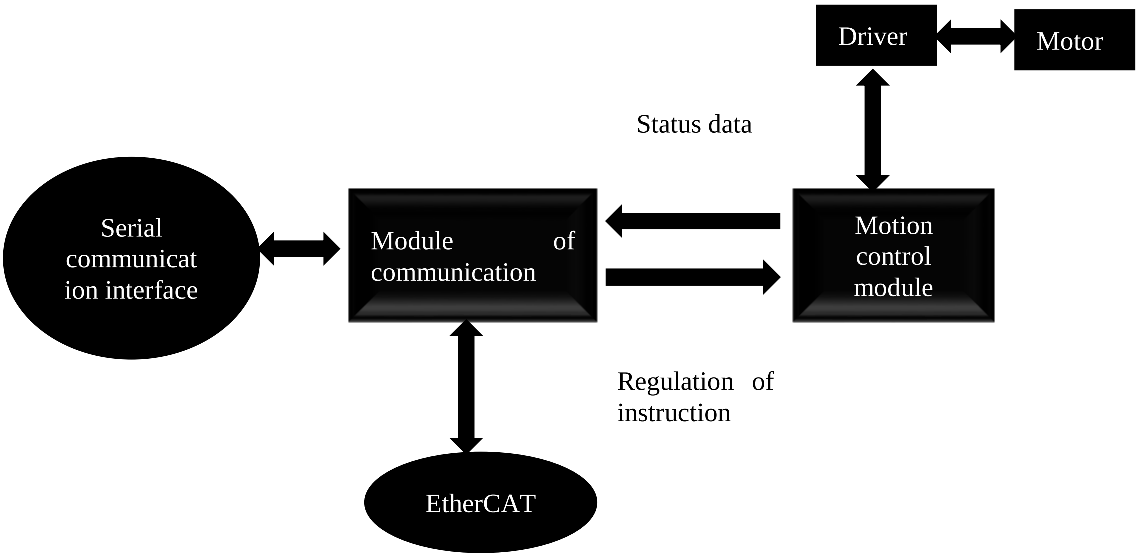

Fig 3. Motion Controller System.

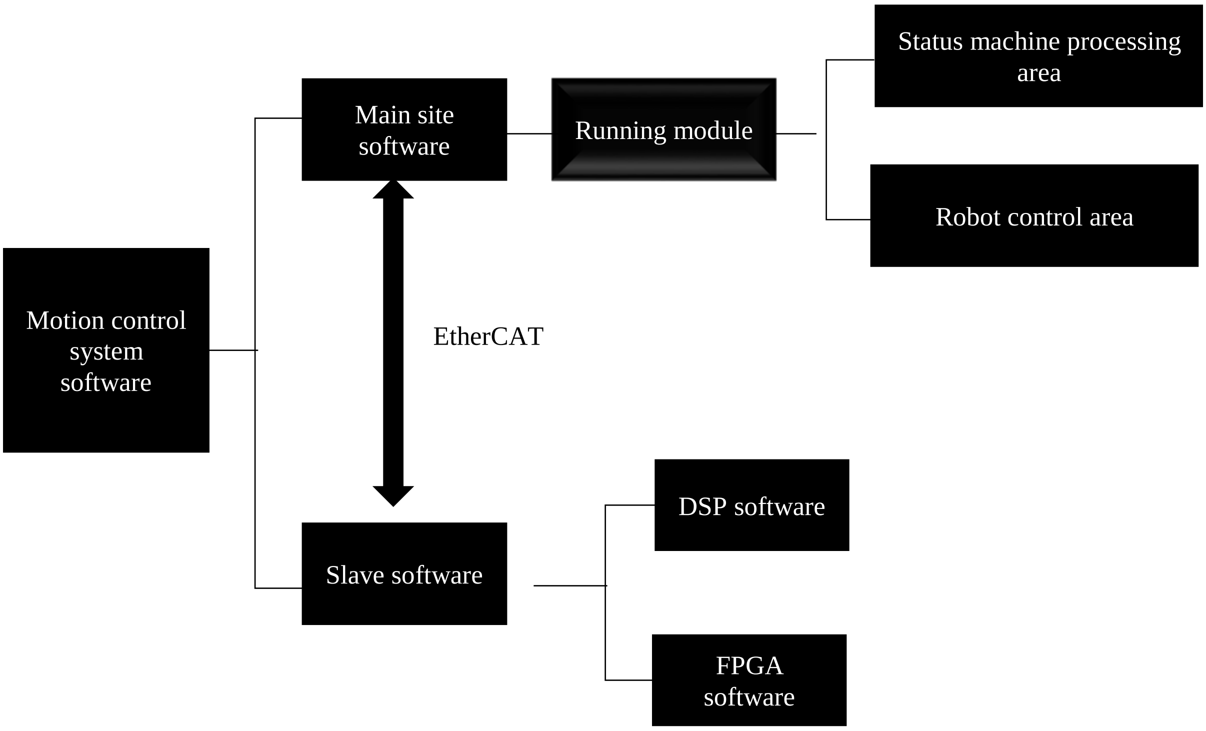

Fig 4. Software Control Model.

Centralized control refers to the use of computer systems for the purpose of overseeing and managing various activities involved in the functioning of firm robots. Centralized control is an initial stage of advancement that requires a significant degree of multifunctionality and computational capability. Historically, the advancement of conventional computer technology was constrained, leading to incomplete refinement of several applications and subsequently, elevated manufacturing prices for diverse equipment kinds. The use of centralized control offers greater economic and operational efficiency. Nevertheless, there is a pressing requirement to enhance the velocity of centralized control and optimize the fundamental internal framework. As a result, the utilization of this particular structure control technique is gradually diminishing in light of the rapid progression of technologies.

Industrial robots are mostly governed by a dispersed framework in their present operational operations. The management system has two distinct components, which center on the principal function and the effective administration of many systems. The process of interpolating trajectories is allocated a certain budget, and numerous coordinates are transformed accordingly. In the subsequent stage of the module, an increased number of central processing units (CPUs) are present, with each CPU responsible for controlling the various joints. This allocation of processors enables the efficient execution of control duties. This approach boosts the efficiency of control, advances the process of control, and ensures a reliable link between the higher-level computer and the microprocessor, primarily via the use of the bus application technique.

III. PERFORMANCE/COST-DRIVEN ROBOT CONTROL DEVELOPMENT

The financial constraints faced by manufacturers of industrial robots necessitate the search for more economical components, leading to the development of robots with increased variability in static and dynamic model parameters. Consequently, these robots exhibit higher levels of noise and disturbances, a greater number of mechanical vibration modes, lower mechanical eigenfrequencies, and larger non-linearities. To ensure the maintenance and potential enhancement of robot performance amidst the cost-centric evolution of robotic development, it becomes imperative to augment the scale of robot models and implement intricate multi-variable control mechanisms. Thus far, it has proven feasible to enhance the current model-based control in order to meet the specified criteria. However, in the context of high-performance applications, it is sometimes necessary to use some sort of model parameter adaptation to address the growing uncertainty associated with the model parameters. Currently, it is possible to generate the tool load parameters, friction model parameters, and kinematics model parameters. The parameters may be periodically adjusted throughout the robot's job execution to account for factors such as temperature drift in the kinematics model parameters.

Offline programming tools play a crucial role in minimizing the expenses associated with the installation and programming of robots. In this context, the trajectories of the tools are optimized with the goal of minimizing the time required for robot movement. This optimization process takes place inside a computer-aided design (CAD) environment. The optimization process must take into account many factors such as collisions, joint working ranges, singularities, and robot dynamics. Ensuring precise replication of programmed movements on the controller is crucial when transferring the optimized program. This task presents particular challenges in handling singularities, controlling robot configuration, interpolating trajectories, and calculating servo references. The optimal approach to address this issue is using identical motion control software in both the off-line software and the robot controller RobotStudio [9], as seen in **Fig 5**.

In order to effectively deploy this method, it is crucial to maintain precise administration of the software version. This entails ensuring that every change to the controllers of robot models and robot control algorithms is likewise reflected in the off-line programming tool. In some cases, the feasibility of using off-line programming as a means to minimize programming expenses may be limited. This might arise due to the unavailability of CAD models or insufficient resources to facilitate off-line programming and robot cell calibration. There is a want for additional approaches to decrease the duration of programming, particularly when dealing with objects that possess intricate geometries. This is often seen in tasks such as grinding, deburring, deflashing, polishing, and milling, as highlighted by Song et al. [10].

Fig 5. Programming ABB Robots using the ABB RobotStudio IDE.

Fig 6. A Gantry-Tau prototype as part of the SMErobot TM Initiative.

One potential approach is to use robot impedance control for the purpose of facilitating intuitive and efficient programming by direct contact with the tool. This method is often referred to as lead through programming, as shown in the SMErobot [11] system, as seen in **Fig 6**. To achieve optimal communication between the programmer and the robot, it is essential to use a 6 DOF force/torque sensor, such as the one developed by [12], which should be positioned between the tool and the wrist flange of the robot. In order to provide prompt and discernible robot responses during human interaction, it is essential to ensure that impedance control has a maximized bandwidth while maintaining stability, even while the robot's tool is in touch with work items during programming. Efficient integration of impedance control with the model-based control of the robot is necessary to accomplish this objective. Despite the current great dependability of robots, customers are displaying a growing inclination towards fault detection, fault isolation, and diagnosis. This interest stems from the need to minimize financial losses caused by production interruptions and to optimize asset management via fast recovery processes.

In order to include residuals, observers, and identification algorithms, it is necessary to use models, as stated by Jeong, Park, Park, Min, and Lee [13]. The real-time dynamic robot models used for robot motion control may likewise be utilized for these methods. When it comes to diagnosing situations when it is necessary to identify trends in crucial parameters, it is commonly found that the level of model excitation achieved during the routine execution of a robot program is insufficient. Subsequently, it will be imperative to execute certain maneuvers at designated temporal intervals, inevitably resulting in a decrease in the efficiency of the robotic systems. The execution of these unique actions necessitates an additional exertion in programming, with the need of an unoccupied workspace for their implementation.

In addition to insufficient excitation, it is worth noting that model parameters may exhibit significant changes even in the absence of defects. These variations might arise from factors such as temperature fluctuations and variations in arm loads. Hence, it is crucial to not only monitor individual parameters, but also the interplay between dynamic parameters, such as predicted joint torques or power levels of the motors, and speed reducers. This is particularly significant when these relationships cannot be included into the diagnostic algorithms' models. In addition to achieving excellent robot control, it is essential to prioritize the optimization of the robot's design in order to reduce its associated costs. In order to achieve this objective, the design of the robot may be developed by incorporating the principles of kinematics and dynamic models used in the controller, alongside the utilization of the remaining motion control software.

The drive line, which encompasses gear boxes, motors, drive units, and rectifiers, represents a significant expenditure in the construction of a robot. Consequently, it is essential for the design process to identify the most economically efficient configuration for the drive line. Typically, the design of a robot follows an iterative process, beginning with the development of kinematics design to determine the desired workspace of the robot. This is followed by the design of rigid multi-body dynamics, which aims to identify the necessary joint torque and power requirements. Finally, the flexible multi-body dynamics design is conducted to ensure that the mechanical bandwidth of the robot is sufficiently high in relation to the servo performance requirements. To optimize the cost of the drive line while adhering to the limits imposed by the multi-body dynamics, a drive line model is included into the dynamic models. The same drive linemodel is executed in real-time inside the controller to determine, for instance, the relationship between joint torques and joint speeds. In the context of real-time dynamic model execution, it is feasible to regulate the velocity and acceleration of the robot in a manner that restricts the occurrence of excessive torques and forces on the various components and structures of the robot.

By using the dynamic load restricted control, it is possible to enhance the average speed and acceleration capabilities of the robot, hence enabling the creation of a more efficient robot design. The aforementioned concept may also be used to the mechanical lifespan management of a robot. By including a real-time thermal model of the robot, the motion control system can effectively restrict the temperature of the motors during robot operation. The adoption of model-based design is essential for achieving a combination of cheap robot cost, excellent robot performance, reduced development cost, faster product cycles, and increased drive line utilization.

IV. ROBOT CONTROL DEVELOPMENT DRIVEN BY AUTOMATION TECHNOLOGY

The concept of humanoid or animal-like machines has captivated humanity for millennia. However, it was not until the 16th century that technological and artisanal advancements in Europe and Japan reached a level where the building of automated dolls became feasible. The term “robots” in contemporary use refers to devices that possess computational intelligence to varying degrees, and the development of such machines has been limited to a relatively short span of a few decades. Industrial robots are now the most prevalent kind of robots in use. They possess use and significance in the manufacturing of commodities, while lacking in intellectual capacity. The development of more advanced computers has paved the way for the creation of more sophisticated artificial entities, such as autonomous cars and service robots. In the forthcoming period, a novel cohort of "personal robots" is anticipated to arise, with the primary objective of furnishing persons with amusement, comfort, and help within the boundaries of their respective residences. At now, the presence of robotic waiters or butlers is confined to nascent prototypes that are mostly housed within certain research establishments. Nevertheless, it is expected that in the forthcoming years, their ubiquity will match that of personal computers.

The term "robot" exhibits a lack of precise definition; yet, it is commonly interpreted as denoting a programmed apparatus that emulates the actions or physical attributes of an intelligent entity, frequently resembling a human being. In order to satisfy the requirements for classification as a robot, a machine must exhibit two fundamental capabilities. First and foremost, the entity should demonstrate the capacity to gather and analyze data from its immediate surroundings. Additionally, it is imperative that the system have the ability to execute tangible tasks, including but not limited to locomotion and object handling. Robotic systems encompass a diverse spectrum of dimensions, spanning from immense apparatuses reaching up to 50 meters in length to little manipulators specifically engineered for operation within micro- or nano-meter scales. Artificial agents has the capability to demonstrate intelligence and manifest independent behavior in accordance with their environment.

On the other hand, individuals may have a deficiency in cognitive abilities, manifesting as mechanistic entities that continually execute predictable and exact behaviors devoid of any deviation. Artificial agents have the capacity to demonstrate behavior that is on a continuum between the aforementioned extremes. Robotic systems have the capability to be propelled by several mechanisms, including but not limited to wheels, tracks, or legs. These systems find use in many settings such as deep sea, laboratories, outer space, workplaces, and museums. Robots are designed and developed with the primary objective of doing tasks that are considered to be arduous, monotonous, or hazardous in nature. Additionally, there has been a new trend in using robots for recreational purposes, such as entertainment and interactive play. They engage in the processes of construction, assembly, cutting, gluing, soldering, welding, painting, inspecting, measuring, digging, demining, harvesting, cleaning, mowing, participating in soccer, and acting in movies. The population of this “multi-cultural society” has seen significant growth in recent years, surpassing one million individuals.

Robotic entities hold significant significance as integral constituents within automation systems, and novel advancements at the system level often engender fresh prerequisites concerning the supervision of robots. Occasionally, the implementation of novel automation ideas necessitates significant modifications in the design of robot control systems. This is shown by automation concepts that rely on the use of collaborative robots, as discussed by [14]. The industrial sector has implemented this particular idea in order to enhance the flexibility associated with the establishment and modification of production lines. Additionally, it aims to improve productivity via the implementation of more effective execution of robot tasks. A sophisticated configuration may include the use of two or more robots operating simultaneously on a workpiece that is being held by another robot, as seen in **Fig 7**. Two examples of applications in the field of welding are arc welding and spot welding.

The primary obstacles in robot control pertain to the structure of the motion control software. This software must possess the capability to generate precise servo references for various robots, ensuring accurate timing. Additionally, it must facilitate seamless and rapid transitions between coordinated and independent robot motions. Furthermore, the software should enable effective recovery from failures, while preventing collisions among collaborating robots. Due to the serial connection of kinematics chains in collaborative robots, the presence of errors in the robot models and serve loops might result in larger posture variations between the tool and the work item compared to single robot installations. Therefore, the implementation of collaborative robotics necessitates enhanced precision in kinetic models, servo loops, feed-forward computations, dynamic models, and servo references.

A further instance in which the notions of robot automation drive the development of robot control is shown by the implementation of robot installations that prioritize enhanced safety standards, as demonstrated by the introduction of Safe Move in 2008 [15]. One driving force behind this advancement is the potential to substitute electrical and mechanical components that restrict the range of work with software limits that ensure safety. This enables a more precise adjustment of a robot's workspace to its surroundings. By adopting this approach, it becomes feasible to include smaller robotic cells, resulting in cost-effective and adaptable robot installations. Another incentive for implementing safe control is to enable human-robot cooperation during regular robot job execution, hence enhancing the adaptability of robot automation. To provide safe control, it is necessary to create residuals that may be used to monitor various aspects such as robot job requirements, interpolated trajectories, servo references, and measured joint positions.

In order to achieve this objective, it is essential to establish an autonomous robot control system that operates concurrently with the primary control software on a secondary computer. This redundant computer must establish secure communication channels to effectively interface with the robot controller. In order to mitigate the excessive expenses associated with simultaneous redundant calculations, it is essential to further minimize the complexity of the dynamic models. Additionally, the use of less precise control ideas should be considered as alternatives to the current servo reference generation and feed-forward control methods.

Nevertheless, when the efficacy of the redundant robot control decreases, it becomes necessary to tolerate greater residual values before triggering an alert. The ability to effectively oversee the safety functionality is crucial in ensuring its reliability during emergency situations. An instance of such oversight is the examination of the mechanical braking systems of the robots. The identification of the brake condition may be achieved by using a friction model for the brakes and controlling the robot joints when the brakes are engaged. Sensors are often used in many robot installations due to the presence of disparities in the position, orientation, and dimensions of items that need to be processed by the robot. In some scenarios, the sensors prompt modifications to the pre-determined trajectory of the robot.

Consequently, the model-based servo reference generator must possess the capability to promptly make adjustments to the servo reference that adhere to dynamic constraints. Instances where the implementation of time critical sensor-controlled motion corrections is necessary include contour tracking for arc welding and robot trajectory compensation for conveyor motions. In some instances, the sensor commands are received after the optimal servo references have been computed. A prevalent challenge encountered in the field of robot automation is to the task of supplying the robot with components. In scenarios involving the segregation of components into pallets or conveyors, cameras may be readily used to provide instructions to the robot on the precise locations from which the components are to be retrieved. However, it is often observed that the various components are typically supplied in containers, necessitating the labor-intensive task of sorting and arranging them into pallets or conveyors, which may either involve a significant amount of manual labor or need the use of costly machinery.

Hence, there exists a significant level of interest within the industrial sector regarding the use of robotic systems for the purpose of bin picking, especially for components that are randomly distributed throughout many levels. According to Zaretskaya [16], as seen in **Fig 8**, the resolution to this issue primarily relies on an advanced visual perception system.

Fig 7. The ABB MultiMove concept is used to operate four cooperative robots. The task is carried out by one robot while three others carry out separate operations on it in a coordinated manner.

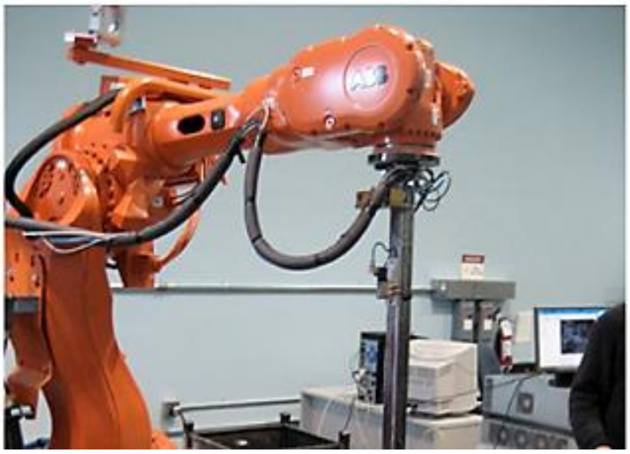

Fig 8. This is an example of a test installation for automatic bin selection. Here, the gripper is mounted on a lengthy beam so it may access all things in the deep bin without touching the walls of the bin or approaching singularities.

Fig 9. Torque converter installation example utilizing force-controlled assemblv.

Fig 10. Installation of a turbine employing force-controlled grinding as an example.

However, there are additional complex challenges that must be addressed in the realm of robot control, since the robot's motions are inherently stochastic, dictated by the instructions provided by the vision system. This implies that the prescribed movements have the potential to encounter singularities, need a transition to a different configuration of the robot arms or wrist, exceed the operational range of a robot joint, or result in collisions with, for instance, the walls of the bin. In order to address the issue of collisions, it is important to execute real-time simulations of the robot and its surrounding environment using geometric models, in conjunction with collision avoidance algorithms. In order to address singularities, one may use functionality for singularity avoidance by adjustments in tool orientation. Additionally, robot configuration changes can be managed through automated analysis of anticipated robot configurations prior to trajectory development.

V. APPLICATION-DRIVEN ROBOT CONTROL DEVELOPMENT

As stated in [17], the current market for robot applications in the automobile sector has reached a saturation point, prompting robot manufacturers to shift their focus towards the development of other applications. Certain applications need significant advancements in robot control development. An illustrative instance in this regard is to the use of robots for the assembly of drive train components in automobiles. This task presents challenges due to the presence of narrow tolerances, resulting in instances when items get entangled with one another during the assembly process. The use of 6 DOF (Degrees Of Freedom) force/torque sensors, as shown by Song, Wu, Gang, and Huang [18], in conjunction with the implementation of admittance control on the robot, has provided evidence that robots are capable of executing challenging assembly jobs at a quicker pace and with reduced mating forces compared to hand assembly, as seen by Javaid, Haleem, Singh, and Suman [19] (see **Fig 9**). The effectiveness of the assembly process is contingent upon not just the use of a high bandwidth sensor loop, but also the careful consideration of the movement pattern employed. In order to minimize delay time after the detection of a contact force, it is crucial to implement control techniques at a high bandwidth and sampling frequency.

There has been a notable rise in the use of robots in mechanical machining applications, particularly for materials such as plastics and aluminum that do not possess high levels of hardness. Processes such as grinding, deburring, and polishing are often used, although drilling and milling are less prevalent because to the increased demands on manipulator stiffness, bandwidth, and precision. The use of robots in machining applications is motivated by their cost-effectiveness and enhanced adaptability as compared to CNC machines. The process of machining often necessitates precise management of tool forces. Consequently, the use of 6 degrees of freedom (DOF) force sensors for force control is advantageous in this context. It is worth noting that the control tactics employed in machining vary significantly from those employed in assembly, as seen in **Fig 10**. In addition to using the force control loop to regulate the force component perpendicular to the trajectory, there are instances when the measured force along the trajectory is used to govern the velocity of the robot. Laser cutting is an additional application that has shown a need for further advancement in robot control.

In the context of mechanical machining, the use of robots for laser cutting is primarily motivated by the advantages of reduced cost and more flexibility as compared to CNC machines. A noteworthy advancement in the field of robotic laser cutting was instigated by the shift from welded to hydro-formed beams in the frames of automobiles inside the United States. The implementation of this shift rendered the act of creating apertures in the frames by punching infeasible, hence necessitating the use of laser cutting technology by American automobile manufacturers non their production processes. In order to circumvent the need for costly massive Cartesian manipulators, automobile manufacturers sought a solution for achieving precise robot laser cutting. Through the use of Iterative Learning Control [20] in conjunction with model-based control, it was discovered that this objective could be accomplished. The learning process included both the estimation of dynamic model parameters and the analysis of observed route data. The learning process effectively addressed errors arising from friction-induced route deviations and model flaws related to both kinematics and dynamics.

VI. CONCLUSIONS

Various components make up the Industrial Robot Control (IRC) system, including sensors, computers, axis controllers, auxiliary equipment, and a demonstration box. A central command center for monitoring the robot's actions is the control computer, while the sensors allow for the regulation and administration of the robotic system. The robot's speed and the execution of certain operations are controlled by the axis controllers. Robot control systems have had to evolve to keep up with the increasing automation in industry. The personal computer (PC) serves as an intermediary between people and machines, facilitating the exchange of information. In contrast, the motion controller is responsible for executing intricate mathematical operations. The use of Industrial Ethernet technology offers a viable resolution to the issues arising from the proliferation of cables and interference. Actuators play a crucial role in the regulation of particular locations within the realm of industrial robots, where precise torque control is vital for the successful execution of manipulation and assembly operations. The software system is comprised of two components: the master software and the slave software. The master software functions on a personal computer.

The establishment of centralized control plays a pivotal role in the advancement of industrial robot development, whereby the allocation of processors is undertaken to enhance the efficiency of control mechanisms. Offline programming solutions are effective in reducing expenses related to the installation and programming of robots. Impedance control and model-based control play a crucial role in facilitating intuitive programming and enhancing efficient communication with the robot. The identification and diagnosis of faults are subjects of interest in order to mitigate financial losses and enhance the efficiency of asset management. Motion control in robotics often relies on the use of real-time dynamic robot models. By improving the design of the robot, it is possible to achieve cost reduction. The use of model-based design is vital in order to attain a harmonious balance between cost, performance, and development efficiency. Robots are robots that have been designed to imitate the actions or physical attributes of sentient animals. They may be propelled by diverse mechanisms and used in diverse settings. The primary objective of collaborative robots is to augment both flexibility and productivity.

The use of advanced safety protocols, such as Safe Move, facilitates the ability to finely calibrate the operational environment of a robotic system. Ensuring safety control necessitates the vigilant monitoring of several facets and the establishment of secure routes for communication. Sensors play a crucial role in robot installations, as they enable the system to gather and process relevant data. In order to ensure optimal performance, model-based servo reference generators are required to rapidly make necessary modifications based on the information provided by the sensors. The implementation of robot automation encounters difficulties in the areas of component supply and bin selecting. The automotive industry has stimulated the attention of robot makers towards other uses, namely in the areas of assembly and machining. The progress of robot control in laser cutting technology necessitates additional development. In general, the development of sophisticated control systems for robots is imperative in order to fulfill the requirements of automated industries and enhance effectiveness and productivity in many applications.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests

There are no competing interests.

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