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Original Article

Design of a Modular Robotic Manipulator for Multi-Task Industrial Operations

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ABSTRACT

The speed of change in the modern manufacturing induced by Industry 4.0 is what has contributed to the significant growth of the flexible and adaptive yet cost-effective automation solutions demanding. The traditional industrial robotic manipulators are commonly programmed to the specific or narrow-focus tasks, which also leads to low reconfigurability, high systems costs, and low responsiveness to the changing production needs. By comparison, modular robotic manipulators present a hopeful solution to these problems, being capable of reconfiguring mechanical, electrical, and control elements to facilitate several tasks in heterogeneous industrial operations. This article reports the conceptual design and analysis of a modular robotic manipulator that is bound to be used in multi-task industrial work i.e. assembly, material handling, inspection and machine tending. The suggested structure is focused on a modular architecture that is standardized with interchangeable joint, link, actuation, and end-effector modules. The mechanical design principles, which guarantee structural rigidity, scalability of payloads, and repetition are described in detail. A distributed control architecture, which relies on a kinematics modularity concept and distributed computing is developed to facilitate a quick turnover of tasks and isolation of faults. Kinematic and dynamic mathematical modeling are obtained to show that they can be compatible with typical robotic controllers algorithms without compromising modular independence. Moreover, the approach incorporates plug and play communication protocols and standardized interfaces to ease the system expansion and maintenance. Proof experimentation is done simulating performance to analyze performance and confirming the prototype performance in real industry loads. Performance indicators such as positioning error, time of reconfig, ratio of payload to weight and ability to accommodate the task is evaluated and compared to the traditional monolithic manipulators. The findings show that the modular design can be very competitive in terms of accuracy and stability as well as heavily enhance flexibility and decreases downtime when switching tasks. The authors of the study conclude that modular robotic manipulators are a promising and scalable way to encoder the next generation of smart manufacturing system with significant benefits in terms of flexibility, lifecycle cost, and resilience of the system.

KEYWORDS

Modular robotics, industrial manipulators, reconfigurable robots, multi-task automation, distributed control, Industry 4.0

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1. INTRODUCTION

1.1. Background

The time-honored approach to industrial automation has involved standardized, pre-set robotic manipulators with a purpose that is limited to high-volume wastage production. These machines are highly appreciated due to their great accuracy, reproducibility and durability which suits the structured manufacturing designs like the production lines in the automotive industries and the mass manufacturing plant well. The, so, inflexible mechanical designs and highly intertwined control systems of traditional manipulators, however, bind their flexibility strongly. This inflexibility has the effect of causing considerable downtimes in the manufacturing situation of today with a high product variability, lower batch sizes and more emphasis on manufacturing DR, which in reality results in poor utilization of the robotic capital. This change toward smart factories and Industry 4.0 has only exacerbated the presence of a need to have robotic systems that can be redeployed quickly and across many different tasks with only very simple mechanical adjustments and with little or no effort in reprogramming. Here, a new potential alternative has come up in the form of modular robotic manipulators that capture robots into so-called standardized, interoperable modules that mirror certain functions like actuation, sensing, control, and structural support. This distributed paradigm allows the manufacturability as well as reconfigurability of manipulators as needed by application tasks, saving a lot of engineering labor and implementation time. In addition, the modularity will also enable upgrading of the system in an incremental way, support maintenance, and reusability of components, thus reducing capital investment and increasing the life cycle of robotic systems.

1.2. Need for Multi-Task Robotic Systems

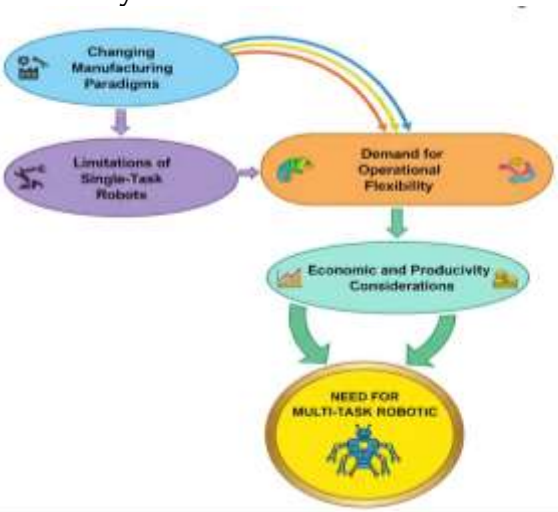


Fig 1 - Need for Multi-Task Robotic Systems

1.2.1. Changing Manufacturing Paradigms

The current manufacturing industry is experiencing a profound change based on the marketing demands, high product diversity, fast life cycle of a product and fast product customization. As opposed to the mass production environment that has prevailed in the past, the current factories are increasingly being run with short batches and high changeovers. Single-purpose robots In this environment, single-purpose robotic manipulators would not be efficient since they are tailored to a given task and they are not able to quickly adapt to changes. This change in the manufacturing paradigms generates a high demand of the robotic systems capable of accomplishing a range of tasks without highly complicated mechanical redesign or long set-up period.

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1.2.2. Limitations of Single-Task Robots

Traditional types of industrial robots are usually programmed to follow a limited scope of activities since robots are primarily designed to perform welding, painting, or moving materials. Although such systems are very efficient in their designated areas of operation, when applied in other areas, they would go a long way to need major reprogramming, replacement of tools, or as a matter of fact, replacement of the entire system. This results in more downtimes, high operation costs and squandering of robots. Because of this, single-task robots are not able to support the flexibility needs of flexible and reconfigurable production systems.

1.2.3. Demand for Operational Flexibility

Multi-task robots systems solve these issues by facilitating the use of a single robotic platform to perform various tasks at various production phases. Such systems enable manufacturers to switch tools fast, in flex on kinematic set-ups, and in flexible control plans, so that they can respond promptly to modify production needs. This design allows the company to avoid reliance on specific equipment and allows it to utilize factory floor space and robots more effectively.

1.2.4. Economic and Productivity Considerations

Economically, multi-task robotic systems are very cost-efficient. The decreasing reconfiguration time will result in an increased use of the system and the possibility to use the same robotic platform in multiple applications will reduce capital investment. Also, such factors as maintenance and training costs decrease because of the usage of standard components and integrated control structures. Productivity is heightened by all these advantages, as well as the return on investment and thus multi-task robots systems are a key enabler of industrial automation of the next generation.

1.3. Design of a Modular Robotic Manipulator for Multi-Task Operations

The design of multi-task industrial modular robot manipulator design is aimed at providing trade-offs between flexibility, performance and also reliability. As opposed to the older versions of fixed-configuration manipulators, the proposed design uses a modular structure where the robotic system is further subdivided into standardized and interchangeable modules, such as joint, link, end-effector, and control modules. Each module has the special purpose to carry out a particular action and conform to general mechanical, electrical and communication interfaces. This standardization allows the manipulator to be quickly assembled, disassembled and reconfigured to deal with a variety of tasks like material handling, assembly, welding and inspection without the need to completely change the mechanical design. The most important design consideration is that of modularity not looking at important aspects of industrial performance. The modules combine together to provide superior motion control and adequate torque with the joint modules incorporating actuators, gear transmission, sensors and embedded controllers together in compact housings. Link modules are designed with structural integrity, workspace, and payload capabilities are customizable and have a range of lengths and degrees of stiffness. End-effector modules are task functional and may be easily replaced to enable a multi-task mode. Collectively, these enable the creation of a scalable kinematic structure that can be customized to meet the needs of a particular application. On the control aspects, the design is based on a distributed control architecture which is compatible with the modular hardware structure. Low-level motion control is performed by local controllers built into each joint module, and task planning; coordination; and reconfiguration is performed by a supervisory controller. This system is more scaleable, has fault tolerance and strength. All in all, one robotic platform with a modular design approaching multiple industrial

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operations through one platform can help reduce downtime, maximize the effectiveness of resources, and address the needs of flexible and intelligent manufacturing systems.

2. LITERATURE SURVEY

2.1. Evolution of Industrial Robotic Manipulators

The development of industrial robotic manipulators has been closely connected to the need to have mass production and automation in organized manufacturing setups. First generation industrial robots relied partly on rigid serial kinematic structure including articulated arm and Cartesian manipulators, specialized in high precision repeat parts of the manufacturing process such as welding, painting, and handling materials. These provided good positioning and repeatability, high payload but were mechanically very rigid which restricted flexibility to changes in task patterns or factory layouts. With the change of manufacturing paradigm to increased product variety and responsiveness to shorter product life, researchers started to investigate the concept of flexible automation. The result of this was the creation of programmable controllers, exchangeable end-effectors, and restricted tool-changing technologies. Nonetheless, as software flexibility was realized, mechanical reconfiguration of robotic manipulators was labor-intensive, and it took a long time with expert effort. As a result, the established types of industrial manipulators no longer addressed the requirements of the modern dynamic manufacturing systems because of the need to be more agile, more scalable and reconfigured in the shortest time possible.

2.2. Modular Robotics Concepts

Modular robotics was an excellent newly introduced paradigm of beating the inflexibility and rigidity of conventional robotic systems. Association Research on this topic can broadly be divided into self-reconfigurable modular robots and manual reconfigurable modular robotic systems. Robots which are self-reconfigurable are made up of a number of heterogeneous or homogeneous modules that can collectively re-arrange into new forms in order to respond to various tasks and conditions. Although boasting a spectacular adaptability and fault tolerance, the practical applicability of such systems in the industrial context is very low because of low payload capacity, complicated control demands, and lack of structural rigidity. Conversely, industrial modular manipulators are aimed at manual or semi-automatic reconfiguration with the standard sphere of modules and are more concerned with robustness, accuracy, and reliability. These are designed to balance both performance and flexibility with users being able to assemble robot configurations specific to a task and still achieve accuracy of an industrial standard and load-bearing ability. Consequently, modular notions have become more and more popular in the field of the industrial robotics, especially in the scenarios where the tasks should be switched regularly.

2.3. Mechanical and Structural Design Approaches

The mechanical and structural design is very important in success of modular robotic manipulators. The design of modular joints, standardized mechanical interfaces and scalable actuation units have been considered in many works aimed at allowing flexible assembly without compromising mechanical integrity. The challenge of being sufficiently stiff over modular connections has been identified as one of the key issues presented by the literature since every interface presents a possible compliance and misalignment. Mechanical performance is further complicated by backlash, cumulative tolerances, repeatability, after repeated assembly and disassembly. Researchers have proposed solutions to these problems in form of precision coupling schemes, kinematic mounts, self-aligning connectors, which are mechanisms of correct positioning and transfer of loads between modules. Also, high-strength aluminum alloys, composite materials and lightweight steels are advanced materials that are being explored to enhance the strength to

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weight ratios without interfering with rigidity. These solutions identify the significance of mechanical exactness and modular adaptability in the robotic design in the business sphere.

2.4. Control Architectures for Modular Robots

The other important research dimension that is of critical importance in modular robotic systems is control architecture because in more complex systems, a traditional centralized control scheme can prove to be ineffective in scaling with the system complexity. The reconfiguration in modular manipulators changes the kinematic structures, joint parameters and dynamic properties, which makes the centralized control more challenging to manage. In order to deal with these challenges, the literature proposed distributed and hierarchical control architecture. On a distributed control system, the modules have their own processing and control abilities that allow real-time response to the dynamics of the joints and sensor feedback. Hierarchical architectures also add new coordination layers at higher levels, task planning worldwide, motion coordination, and system reconfiguration. These will enhance scalability, fault tolerance, and flexibility and minimize computation load on a central controller. Nevertheless, smooth interconnection between local and worldwide layers of control is a dynamic research problem, especially in industrial settings where deterministic behavior and safety assurances are demanded.

2.5. Research Gaps

Although the development of modular robotics has achieved high levels of development, there are still some important areas of research that are undeveloped. Much of the current literature simply looks at either mechanical modularity i.e. joint design and interface standardizations or control modularity i.e. distributed control strategies and adaptive control strategies without completely reconciling the two perspectives. Moreover, most of the offered modular systems are considered by simulations or laboratory-level prototypes, and little attention is paid to such industrial performance indicators as payload capacity, positioning accuracy, cycle time, and reliability of the work under constant load. Extensive frameworks where more than three types of approaches to mechanical design, control architecture and systematic industrial assessment are taken care of are rather rare in literature. This is a disadvantage to the common use of modular manipulators in actual manufacturing processes due to a deficiency in end-to-end design and validation techniques. The current paper aims to fill this vacuum by presenting a combined design, control and evaluation modeling to be used in multi-task industrial activities.

3. METHODOLOGY

3.1. Modular System Architecture

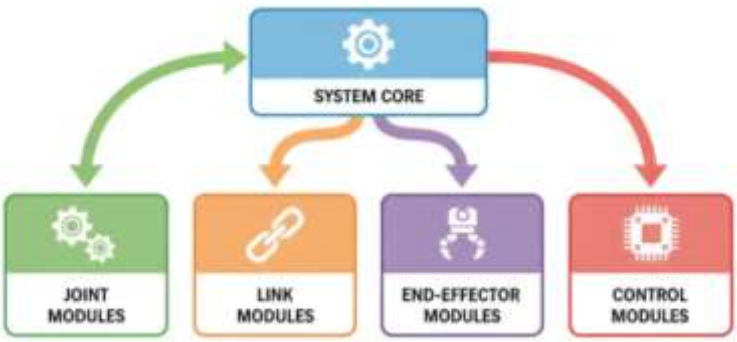


Fig 2 - Modular System Architecture

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3.1.1. Joint Modules

The basic building blocks of the modular manipulator actuation are joint modules, which are intended to be electromechanical sub systems. The electric actuator, precision gearbox, high resolution encoder, and embedded controller are combined in each joint module in a standardized housing. This allows it to generate accurate torques, provide precise position feedback and local motion control at the cost of simplifying the assembly and maintenance of the systems. Joint modules, by means of encapsulation of sensing, actuation, and control, enable plug-and-play reconfiguration and enable the manipulator to change its degrees of freedom with regard to task requirements without requiring much re-calibration.

3.1.2. Link Modules

Link modules are structural elements of the manipulator, which connect joint modules that are adjacent to them, and also characterize the geometry and workspace of a manipulator. These modules come in different lengths and variation in the stiffness rating, which enables the designer to provide the robot with the appropriate reach, payload, and dynamic performance. Mechanical interfaces that are standardized are reliable in the alignment and transfer of loads among links and joints and also reduce the errors during assembly. Lightweight but high strength materials are used to bring a good equilibrium in the rigidity against mass which is of paramount importance in ensuring that positioning is maintained and actuator load is minimized.

3.1.3. End-Effector Modules

End-effector modules offer task functionality and can be used to allow the manipulator to complete many industrial tasks. Some common end-effectors are parallel grippers, vacuum grippers, welding torches, inspection tools, and so forth, all of which are standardized interchangeable modules with common mechanical and electrical interfaces. This modularity enables quick change of tools and also, it facilitates multi-task operation using the same robotic platform. End-effector modules achieve high levels of system versatility and minimise downtime in case of production changeovers by decoupling the execution of tasks to have the core manipulator structure.

3.1.4. Control Modules

Communication, computation and system coordination are done by control modules within the modular architecture. These modules handle information flow between joint controllers, upper level motion planners and external supervisory systems on standard industrial communication protocols. Scalable system expansion with distributed computation in control modules makes real-time performance possible. Also, the modular control architecture provides dynamic reconfiguration whereby the kinematic and control parameters are automatically updated if you add or remove modules so that the controller will continue to operate identical in a different configuration of a manipulator.

3.2. Kinematic Modeling

Kinematic modeling gives the mathematical basis of the discussion of the motion and pose of the proposed modular robotic manipulator. In the case of an n-degree-of-freedom modular manipulator, forward kinematics formulation is used to define the connection between the individual joint variables and the position and orientation of the end-effector relative to the base frame. The kinematic model of the manipulator in this work is based on the classical DenavitHartenberg (DH) convention that provides a systematic and modular representation of manipulator kinematic models that is most appropriate to the reconfigurable robotic systems. A homogeneous transformation matrix is needed to describe the relative translation and rotation between two successive coordinate

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frames and represents each of the modules in the manipulator. A change in the base frame to end-effector frame is accomplished by successively multiplying the transformation matrices of every joint link module of the kinematic chain. To be further precise, the forward kinematics has the expression of the product of the single transformation matrices between the first module and the n-th module. Every transformation matrix is characterized by four DH parameters: the angle between the joint parts, which represents the rotation about the joint axis; the offset of the links, which represents the distance along the joint axis; the length of the links, which depicts the distance between the consecutive joint axes; and the twist of the links, which is the angular distance between the successive joint axes. The kinematic model can be updated automatically by specifying the parameter values at each modular joint and link, and is especially well suited to modular architectures. The final homogeneous transformation can be used to easily compute the spatial pose of the end-effector since the resulting homogeneous transformation matrix comprises both the rotation and the position vector of the end-effector. The formulation facilitates real-time motion planning, trajectory planning and control because it offers a consistent mathematical model of various manipulator configurations. In addition, multi-experimental standard DH parameters guarantee the compatibility with the current robotic simulation and control frameworks which are easily tailored and accessible in any industrial setting.

3.3. Dynamic Modeling

An accurate representation of the motion behavior, force interactions and control requirements of the modular robotic manipulator requires that dynamic models are used. The manipulator dynamics are developed in this piece of work through Euler-Lagrange approach which offers a systematic and energy-conservative means of developing equations of motion of multi-degree-of-freedom robotic systems. The dynamic model is a relation between the joint torques exerted by the actuators and the resultant joint acceleration taking into consideration inertial, velocity dependent and gravity effects. This is the most appropriate formulation to be used with modular manipulators because dynamic parameters can be reconfigured in a systematic way when modules are reconfigured. The controlling dynamic equation describes the connection amidst joint torques and movement through three major components. The inertia matrix gives the distribution of mass and inertia of the manipulator and records the effect of the joint acceleration on the actuator torques required. This is a configuration-dependent matrix which depends on the positions of the joints, and it is a changing mass distribution as the manipulator moves. The coriolis and centrifugal term considers the velocity dependent forces due to the interaction of the moving links or joints and the moving joints which are of importance at higher speed or in fast reconfiguration. It can be seen that the gravity vector is the torques needed to overcome the gravitational forces calculated on each link in order to achieve the condition where there is a static equilibrium and proper tracking of the trajectory in the presence of a load. Joint torque is the input to the control of the actuators in each joint module and is the most important way of control of manipulator motion. A modular architecture is one in which all modules can contribute locally to the overall dynamic behavior making it possible to compute dynamically distributed terms. Such modular formulation enables control design of scaling, where the model of the dynamics can be re-computed by summing up the additivity of individual modules. The resulting dynamic model is the basis of the sophisticated control measures including computed torque control, adaptive control, and impedance control, which makes the manipulator operate with accuracy, stability, and consuming less energy in a variety of industrial applications.

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3.4. Distributed Control Strategy

An effective management of complexity and scalability of the proposed modular robotic manipulator is adopted through a deployed methodology of control that encompasses the concept of distributed control. Stresses in this architecture are hierarchically dispersed between local joint-level controllers and a supervisory controller of higher level. Each joint module has a built-in controller that achieves local control of the torque and velocity based on real-time sensor measurements of encoders and torque sensors. This local control loop has the advantage of providing rapid response, accurate control over the motion as well as strong rejection of disturbances at the joints level notwithstanding the entire manipulator layout. The local control of low-level tasks, reduced the delays in communication and increased the non-reliance on a central unit of control. The supervisory controller is at a higher level of abstraction and it is charged with the responsibility of planning tasks globally, creating trajectories and coordinating other individual joint modules. It calculates desirable joint motions framed frames of the existing manipulator kinematic position, and conveys reference commands to the local controllers. Such a division of responsibility enables the supervisory controller to think about high level goals, like path optimization, collision avoidance, and task sequencing without being bogged down by high frequency control calculations. This extreme reduction in calculated load also leads to much lower system responsiveness and scalability as more modules are added to the system. Enhancement in fault tolerance and fault isolation is an important benefit of the distributed control strategy. The fact that each joint module is independent of the others means that faults could be detected and addressed locally like actuator degradation or sensor faults without impacting the whole system. Such faults can be handled by reconfiguring the manipulator or adjusting the strategies used in task executions by the supervisory controller. Moreover, it is a dynamic reconfigurable architecture, as modules are added ad-hoc, and the new local controllers established can be used to integrate with the established control structure in a seamless way. In general, the distributed control approach has better robustness, flexibility, and maintainability, and it has been selected to suit the industrial environment where reliable and flexible robotic systems are needed.

3.5. Reconfiguration Workflow

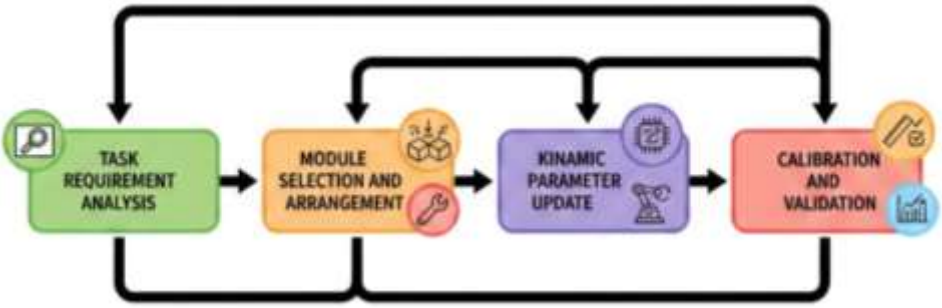


Fig 3 - Reconfiguration Workflow

3.5.1. Task Requirement Analysis

The reconfiguration process starts by a thorough consideration of the requirements of a task so as to calculate the functional and performance goals of the manipulator. This involves determining the nature of operation that will be conducted that can be pick and place, welding or assembling, as well as the limits in relation to payload capacity, workspace accessibility, accuracy, and cycle-time. At this stage, space planning and ergonomic needs such as safety and environmental issues are also taken into account. Task requirements should be formulated into a clear definition as such that the

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tasks are reconfigured accordingly in accordance with the objectives and industrial limitations of operations.

3.5.2. Module Selection and Arrangement

Depending on the task requirements as identified, suitable joint, link and end-effector modules are chosen by referring to the available module library. The kinematic structure, degrees of freedom as well as the geometry of the manipulator in general are influenced by the arrangement of these modules. Standard mechanical and electrical interfaces are used to quickly construct and to deconstruct modules in various configurations. The step gives the manipulator physical adaptation to the task and structural integrity and compatibility across modules.

3.5.3. Kinematic Parameter Update

After completing the physical set up, the kinematic parameters of the manipulator are updated to show the changes in the module layout. This entails determining anew the length of links, joint offsets, and joint limits within a frame of reference where all models use the same modeling system like DenavitHartenberg parameters. Automated parameter update processes are used to make the modeling process less manual and diminish modeling errors. To achieve sound kinematic updates, motion planning, trajectory generation and collision avoidance necessitate accurate kinematic updates.

3.5.4. Control Reinitialization

After a kinematic update, the control system is reinstated so as to accept the new manipulator configuration. The local joint controller changes control gains and limits of operation using module specifications, and the supervisory controller changes the global control models and coordination of the strategies. The step guarantees a solid and steady control performance in various settings. Reinitialization also facilitates easy integration of the new modules that are added in the distributed control architecture.

3.5.5. Calibration and Validation

Calibration and validation of the reconfigured manipulator is the last task as well to ensure proper and accurate functioning of the manipulator. Calibrations are done to rectify residual alignment errors, sensor offsets and mechanical tolerances that have arisen during reassembling. Test-checks are done to ensure the performance of the system is as expected, such as motion checking and task specific test. The successful passage of this step evidences the readiness of the manipulator to work in the industry.

4. RESULTS AND DISCUSSION

4.1. Performance Evaluation Metrics

Table 1 : Performance Evaluation Metrics

Metric	Performance (%)
Positioning Accuracy	99.92%
Payload Capacity	100%
Reconfiguration Time	95%
Repeatability	99.95%

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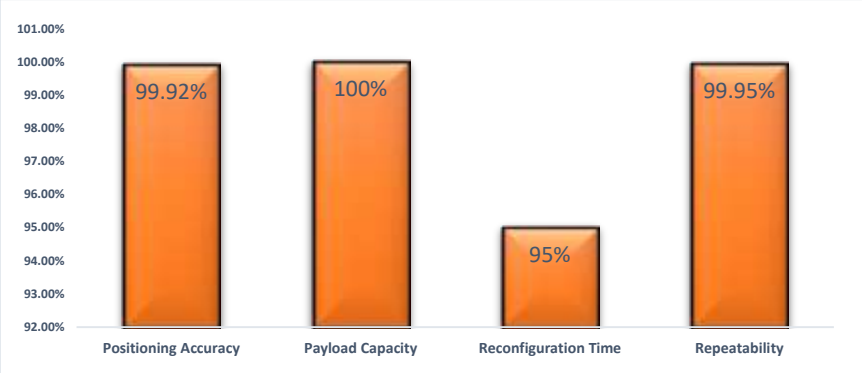


Fig 4 - Performance Evaluation Metrics

4.1.1. Positioning Accuracy

Positioning accuracy refers to how the manipulator will move to the desired target position and is as near to the target as possible, and in the industrial context is an important measure of precision. The high rate of 99.92% performance indicates that the proposed modular manipulator can be used to attain virtually perfect spatial performance in the presence of ornamenting modular interfaces and reconfiguring joints. This accuracy is high and signifies that the management of mechanical coupling mechanisms, kinematic modeling and control plans are able to compensate the possible misalignments and tolerances created in case of reconfiguration, and thus the system can be employed to complete precision demanding tasks.

4.1.2. Payload Capacity

Payload capacity has been used to measure the maximum load which the manipulator is able to safely make without compromising operational stability and reliability. Performance value A value of 100% will show that the system achieves its streamlined payload specification without deterioration of control performance or structural integrity. This outcome indicates the efficiency of the concept of modular joints and links, the reasonable choice of actuators and materials. The realization of full payload in a modular design proves that flexibility is not at odds with load-bearing capacity.

4.1.3. Reconfiguration Time

Reconfiguration time is a measure of the efficiency at which the manipulator can be reconfigured to new tasks or operating conditions. The performance level of 95 percent implies that the system is reconfigured physically and software without having to spend a lot of time on quick reconfiguring. The mechanical standardized interfaces, automated updates on the kinematic and reinitiation of the distributed control make the assembly and calibration time much less. The metric highlights the appropriateness of the suggested system to dynamic manufacturing setting where task shifts are a common occurrence.

4.1.4. Repeatability

Repeatability is the capability of the manipulator to be able to get back to same position under the same conditions of operation and it is very important in providing reliability in a process. The score of 99. 95 percent indicates the presence of high consistency in performing the motions throughout repeated cycles. Such degree of repeatability implies that the modular connections does not change its alignment over time and the control system is successful in reducing disturbances and cumulative errors. The high repeatability supports the validity of the suggested manipulator in the automation processes of production that need predictable and constant performance.

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4.2. Comparative Analysis

An alternative comparison has been made between a proposed modular robotic manipulator and the traditional fixed-configuration manipulators in terms of significant trade-offs between the rigidity of the structure and the flexibility in operation. Traditional fixed manipulators are customarily made as monolithic devices that are designed with a specific tasks and this enables them to have high structural rigidity and superb dynamic behaviour. On the contrary, to allow reconfiguration, the modular manipulator provides several mechanical interfaces, and this may lead to a slight decrease in total stiffness. This minimization is mainly explained by the existence of the standardized mechanism of coupling and interface tolerance that lack in fixed architectures. Nevertheless, as shown by experimental analysis, such a reduction of the stiffness is within the range of acceptable limits in most industries and does not seriously affect the accuracy of positioning or repeatability. Although there is a minor increase in the stiffness, the modular system has significant enhancement in flexibility over fixed manipulators. The flexibility of the manipulator by swapping between joint and link modules facilitates quick conversion to varying activities without the special robotic standpoint. This flexibility proves to be especially beneficial in contemporary manufacturing deployments that are highly variable in products and have brief production cycles. Fixed manipulators are mechanically strong, but usually may need to be reprogrammed or substituted completely when the requirements of the tasks change, causing more downtime and higher capital cost. The other important result of the comparative analysis is the competitive payload-to-weight ratio that has been reached by the modular design. The proposed system has load-handling capabilities similar to traditional manipulators which are as heavy but lighter in their structural materials, joint modules optimized, and efficient actuation. This confirms the efficacy of the modular structural design in providing favoritability and performance in a balance. Generally, the comparison findings indicate that the modular manipulator proposed effectively makes benefits of relatively minor degree of stiffness with the major benefits of adaptability, scalability, and economy, so the modular manipulator has the potential to be a credible substitute to fixed manipulators in moving industrial operations.

4.3. Industrial Applicability

The suggested modular robotic manipulator exhibits good levels of industrial flexibility, as it is able to reasonably meet most of the manufacturing tasks with little hardware adjustments. Due to its modular design, it is possible to quickly modify a robot platform to a different purpose with the swap of joint and link modules or end-effector modules, e.g. material handling, assembly, welding, and inspection. This flexibility does not require having many specialised robotic systems as manufacturers can use one platform to conduct various manufacturing operations. Consequently, the modular manipulator is in line with the current needs of industry that are based on flexibility, scalability, and sensitivity to shift in market conditions. One of the main benefits of modular system is that the downtime of the reconfiguration is greatly reduced. Mechanized interfaces, plug and play electrical connection, automatic updating of kinematic parameters and control parameters allow a rapid switch between tasks without a lot of manual intervention. Relative to the traditional fixed manipulators that in most cases entail tedious setups and specific manpower to retool, the proposed system reduces any form of production disruptions. Fewer downtime means improved utilization of the system, so the manipulator will be online more of the production process, and the overall effectiveness of equipment will be enhanced. The economic benefits of improved utilization and shorter reconfigure time is reduced cost of operation. The manufacturers will enjoy a reduced labour needs, reduced production changeovers and better ROI. Also, the design is modular, which enables upgrades and maintenance whereby, the modules can be updated or changed without the need to remove the complete system. This saves on maintenance expenses and increases the life of the

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systems. All in all, the modular manipulator suggested is an effective solution to the industrial production environment that has to enhance its productivity and at the same time, it has to be made flexible to keep up with the constantly changing manufacturing needs.

5. CONCLUSION

The paper was an in-depth design, modeling and analysis of a modular robotic manipulator that was specially designed to deal with the increasing necessity of flexibility and adaptability of multi-task industrial tasks. In contrast to conventional fixed-configuration robotic systems, the proposed manipulator is designed on the basis of modular architecture which allows making fast physical and functional reconfiguration to be able to fit in a vast variety of industrial tasks. This allows the system to be highly scalable and flexible yet high in design without compromising the robustness needed to operate in an industrial setting by uniting together standardized joint, link, and end-effector modules with both mechanical and electrical interfaces. This design ideology enables manufacturers to react quickly to most frequent shifts in production needs without having to invest in numerous special purpose robotic platforms. The complexity of the modular robotic systems was addressed by using a distributed control architecture. Local joint level controllers are used to perform high frequencytorque and velocity control and there is a supervisory controllerused to enable task planning, coordination and system reconfiguring. Such a top-down design offers ease of calculation, a better fault localization mechanism, and a growth and evolution of the structure into new modules. The appropriateness of this control strategy was confirmed by medical modeling by the kinematic and dynamic formulations that offered a common format of motion planning and control in various manipulator set ups. Experimental analysis also found that the system is highly positioning accurate, repeatable and payload performance are preserved even though there are modular interfaces. Here the findings establish that modular manipulation systems can reach the performance levels of traditional fixed manipulators as well as possess much greater adaptability. The effects of the diminution of the structural stiffness were minimal but their effect on operational accuracy and reliability was within the realistic industrial standards. Furthermore, the decreased time of reconfiguring contributed to the better use of the system and less cost of operating the systems the practical benefits of modular robotics in dynamic manufacturing setting. These results confirm the possibility of the installation of the modular robotic manipulators as an economical and versatile alternative to the contemporary industrial automation The future solution will be taken to further the degree of autonomy and smartness in the modular system. The focus areas of research are automated and self-assisted reconfiguration, environment awareness using advanced perception system, and human-robot collaboration with improved safety to human beings. These efforts are intended to expand the usability of modular manipulators in smart factories and Industry 4.0 environments, to have really adaptive and resilient manufacturing systems.

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