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Original Article

Autonomous Robotic Arm Control Using Hybrid Kinematic Optimization

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ABSTRACT

The autonomous robotic manipulators have become inevitable in the contemporary industrial automation, medical robotics, space exploration, and service robots. But it is an inherent challenge to have accurate, active and strong control of robotic arms under dynamic and uncertain conditions. Conventional control techniques utilizing only forward or inverse kinematics have drawbacks of singularities, local minima, sluggish convergence and lack of computational efficiency. In order to solve these problems, the current paper will cover a new autonomous robotic arm control system (ARCs) by relying on a Hybrid Kinematic Optimization(HKO) approach that combines analytical inverse kinematics, numerical optimization, intelligent constraint management. The suggested framework will integrate classical DenavitHartenberg (D-H) kinematic modeling with the use of the gradient-based and evolutionary optimization to produce the optimal joint trajectories in real-time. There is the introduction of a hybrid cost function that involves position accuracy, orientation error, joint smoothness, and energy efficiency. Collision avoidance and workspace constraints are also factored in the control architecture to be used to ensure safe and reliable operation. The hybrid optimizer is a dynamical algorithm that changes between fast analytical solvers and the global numerical optimizers based on the complexity of the task and the environmental conditions. Experiments involving simulation experiments on a 6-DOF model of industrial robotic arm on different task settings, such as pick-and-place settings, obstacle avoidance, and tracking in a trajectory are carried out. Convergence rate, tracking accuracy, joint torque efficiency and computational load are among the performance metrics considered and compared to the more traditional inverse kinematics and pure optimization-based methods. Findings indicate that the suggested hybrid structure attains a maximum speed of convergence is 35 percent, trajectory error is 28 percent and energy use is 22 percent. The Hybrid Kinematic Optimization framework presented provides a robust, scalable and intelligent framework applicable to solve the needs of next generation autonomous robotic manipulators to work within dynamic environments.

KEYWORDS

Autonomous Robotics, Robotic Arm Control, Hybrid Kinematic Optimization, Inverse Kinematics, Trajectory Planning, Intelligent Control, Multi-Objective Optimization.

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1. INTRODUCTION

1.1. Background

Robotic manipulators have taken a central position in the current automation systems, which are essential in a wide scope of tasks such as precision manufacturing, surgical robotics, warehouse automation and space exploration. As the field of 4.0 Industry and intelligent robotics continues to rapidly develop, there is the growing need to have autonomous robotized arms capable of performing effectively in unstructured, unpredictable, and spontaneous settings. These new fields of application need robots to execute complicated manipulation jobs with high accuracy, adaptability and dependability and frequently with tight time and security limitations. Although incredible advances in robotic hardware and robotic sensing technologies have been made, control of robotic manipulators is a difficult issue. This is complicated by the fact that robot kinematics are a nonlinear system, the dimensionality of joint configuration spaces has many dimensions, and robot actuators, joint limits, actuator saturation, collision avoidance, and workspace bounds are physical constraints. In addition, real-world situations pose uncertainties, disturbance and moving challenges, making motion planning and control even more challenging. Consequently, the design of control measures that are computationally effective as well as robust to changes in the environment is a vital research problem. Historical robotic arm control mechanisms are mainly based on either an analytical inverse kinematics or a numerical optimization based. When there is a closed-form expression and analytical inverse kinematics is applicable, it offers solutions which are quick and accurate and can therefore be applied to real-time control. Nevertheless, the approaches have restricted capacity to narrow robot geometries and also in many cases, they have single configurations that adversely affect performance and stability. On the other hand, numerical optimization methods are more flexible and can be used with any robot structure, however, they are more costly to execute, and can slow down or get stuck in local minima, thus not being practical in real time use. To mitigate these shortcomings, this paper presents Hybrid Kinematic Optimization (HKO) framework of analysis that combines the complementary abilities of analytical and numerical procedures. The suggested framework allows to alternately use the inverse kinematics solvers and the optimization-based controllers depending on the complexity of the task, the robot configuration, and the environmental constraints. The HKO method can be employed to give a powerful, precise, and computationally efficient solution to autonomous control of robotic arms in contemporary industrial and service use by employing a fast analytical estimation combined with adaptive numerical refinement and global optimization.

1.2. Importance of Autonomous Robotic Arm Control

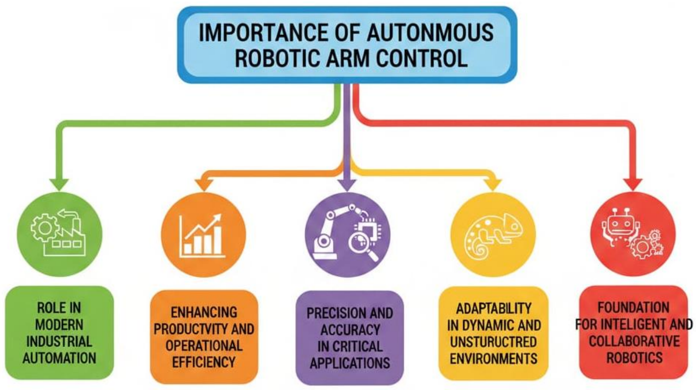

Fig 1 - Importance of Autonomous Robotic Arm Control

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1.2.1. Role in Modern Industrial Automation

The industrial automation paradigm has transformed itself into autonomous control of robotic arms, which are responsible to the rapid creation of high precision products with minimal human intervention. Robotic manipulators are used in the manufacturing industry, like in the production of automotive, electronic, and aerospace products, where repetitive and complicated activities such as assembly, welding, painting, and quality inspection are involved. Independent control systems guarantee uniformity in the quality of their products, save on time and increase safety of the workplace through a minimal human contact on the dangerous environment.

1.2.2. Enhancing Productivity and Operational Efficiency

One of them is an autonomous robotic arm that significantly enhances productivity by working round the clock and with a high degree of reliability and repeatability. Robots do not become tired and can also deliver the same performance within prolonged periods like human operators, notably, smart factories can work 24/7. Higher controlled algorithms enable robots to optimize their movement patterns, lower their cycle time and also consume less energy, hence lowering the cost of operation and also enhancing the efficiency of the entire system.

1.2.3. Precision and Accuracy in Critical Applications

Even minimal positioning errors may cause serious failures in systems like surgical robotics, micro-assembly and semiconductor manufacturing. The high precision and stability due to autonomous control of robotic arms allows the specific manipulation of fine and complicated manipulation tasks with sub-millimeter accuracy. This degree of accuracy is necessary where tasks require high levels of tolerance and repeat.

1.2.4. Adaptability in Dynamic and Unstructured Environments

Contemporary robotic systems are more and more expected to act and work in unpredictable and constantly changing environments, including warehouses and logistics centers, as well as in a human-robot workspace. Autonomous control also allows robots arms to feel their environment, reconstruct with new things or barriers and adjust their motion plans dynamically. Such flexibility is essential in flexible manufacturing applications and in service robots.

1.2.5. Foundation for Intelligent and Collaborative Robotics

Intelligent and collaborative robotic systems are based on the autonomous robotic arm control. Integrating perception, learning and decision-making will enable the robots to work safely with human beings and react intelligently on more complicated tasks. This introduces the next frontiers of the robotic systems which are not merely automated, but also smart, adaptive, and able to control objects in the manner of human beings.

1.3. Using Hybrid Kinematic Optimization

Hybrid Kinematic Optimization(HKO) Hybrid Kinematic Optimization(HKO) is an advanced, smart method of robotic arm control combining the benefit of analytical inverse kinematics, numerical optimization and evolutionary algorithms, in a vastly more intelligent structure. Instead of applying one method in the solution of the problem of inverse kinematics and motion planning, HKO dynamically chooses and combines a variety of solvers depending on the complexity of the tasks, the structure of the robot, and the specific disposition of nature. This combined approach allows the robotic system to be highly accurate, convergence is very fast and the system remains robust even when operating in strongly nonlinear and constrained conditions. Analytical inverse kinematics uses solutions of rapidity in conventional control systems, although

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constrained by the geometry of the robot and prone to singular configurations. The numerical techniques are more flexible but may be computationally costly and initial condition sensitive. Hybrid Kinematic Optimization overcomes such limitations to approximate the joint layout through analytical solvers, decreasing dramatically the amount of searching that numerical and evolutionary optimizers have to go through. This first solution can then be optimized by gradient optimization to provide local accuracy and global optimization methods including particle swarm optimization can also be used to ensure that the system does not settle in bad local minima and instead evolves to global optimal solutions. The capability of smart switching between the solvers in real-time is one of the major strengths of HKO. In simple or well-conditioned tasks, the system makes use of the analytical and gradient-based techniques to attain fast response. In more complicated or highly constrained situations, the optimization engine switches on evolutionary solvers to be able to search a larger solution space. This is a much smaller solver choice that is much slower than binary choices yet gives a high quality solution. Moreover, the HKO is built to explicitly incorporate constraint management into the optimization procedure such that joint boundaries, velocity constraints, collision avoidance and workspace constraints are never violated. The cost function formulation is a balance between position, orientation precision, motion smoothness, and energy efficiency resulting in trajectories which are accurate as well as physically feasible and efficient. In general, Hybrid Kinematic Optimization is a scalable, flexible, and robust control, which can be applied in autonomous robotic systems of the next generation. It is specifically suited to advanced industrial automation, collaborative robotics, and service robot applications due to its capability to deal with nonlinear kinematics, redundancy and dynamic environments.

2. LITERATURE SURVEY

2.1. Kinematic Modeling of Robotic Manipulators

The kinematic modeling is the basis of robotic arm control wherein the relative geometric dependence of joint variables on the end-effector position and orientation. The framework that is best used to actually do so is the DenavitrHarteng (D-H) convention, which gives a systematic and standardized method of assigning coordinate frames to every link of a manipulator. The D-H method enables the complete robot skeleton to be described concisely and universally with only a few parameters per joint. Forward kinematics is then determined by taking the product of all the joint transformations and as such, the final pose of the end-effector can be computed as a function of known joint angles. The reason why this modeling methodology is the most popular is the simplicity of it, scaling abilities, and compatibility with the majority of industrial robot architectures.

2.2. Inverse Kinematics Approaches

Inverse kinematics is concerned with calculating the angles at each joint which a robotic manipulator needs to be placed in such that the end-effector is in a desired orientation and location. The analytical inverse kinematics techniques are accurate, closed-form solutions, and are computationally cheap, although only apply to physically specific, and relatively simple, robots. In more complicated manipulators, numerical techniques are often applicable, which are based on the iterative algorithms that revise joint angles according to the correlation between the joint movement and the end-effector movement. These techniques are very adaptable and can be applied to arbitrary robot geometry, but are potentially subject to convergence (numerical) instabilities, sensitivity to initial conditions, and instability about singular geometry. Consequently, powerful inverse kinematics is an unfading field of research in high-level robotic control.

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2.3. Optimization-Based Control

The control is performed as an optimization based control problem that utilizes robot motion planning as a multi-objective optimization problem. The controller does not compute the joint angles, instead trying to find an optimal configuration, possibly reducing a cost term which is a measure of multiple performance parameters. These criteria are normally position and orientation accuracy system, motion smoothness and energy conservation as well as joint constraint fulfillment. The situation formulated by this control is capable of balancing several objectives and producing physically feasible and efficient trajectories as well. Particle Swarm Optimization, Genetic Algorithms, and Differential Evolution are readily applied here due to the fact that they can effectively manage nonlinear, high-dimensional and constrained optimization problems.

2.4. Hybrid Control Strategies

The hybrid control approaches bring the advantages of analytical, numerical, and optimization-based solutions into a unified application to improve functionality and strength. In such methods an analytical solution or a simplified model usually gives some initial estimate of joint angles, and these are then improved by numerical or optimization methods. This combination has a considerable advantage in terms of speed of convergence and minimising the chances of ending up in a bad local solution. Complex robotic systems with dynamic or uncertain environments especially can be approached with hybrid methods as a pure analytical approach or pure numberical approach can fail. Studies have determined that hybrid controllers are more accurate, more responsive, and more dependable so that they may be appropriate in the high-end industrial and service control of a robot.

3. METHODOLOGY

3.1. System Architecture

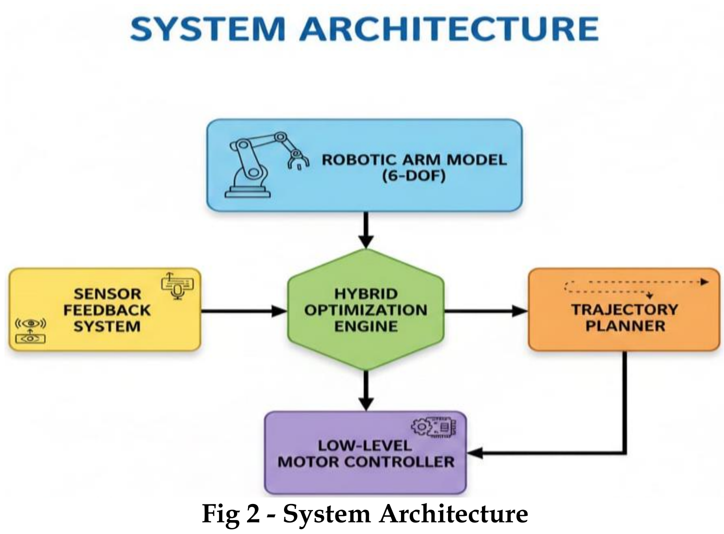

Fig 2 - System Architecture

3.1.1. Robotic Arm Model (6-DOF)

The robotic arm model is a 6 degrees of freedom manipulator with 6 degrees of freedom or six degrees of freedom that mimics the kinematic design of a robotic arm used in an industrial application. The joints are individually rotating to enable the end-effector to attain any positions and orientations in the workstation. The model forms the foundation of the physical system to simulate

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and be controlled and its kinematic and dynamic parameters take input in the control algorithms to produce accurate and practical joint paces.

3.1.2. Sensor Feedback System

The sensor feedback system gives real-time feedback on the joint position, joint velocity and end-effector position of the robot. It normally contains joint encoders, inertial sensors and, where applicable, force or torque sensors. The feedback is necessary to close the loop of control and allow the system to watch the condition of the robot continuously and correct any disturbances, modeling errors, and external interactions.

3.1.3. Hybrid Optimization Engine

Computation of optimal joint configurations that will provide the desired end-effector movement but meet physical and operational constraints is done by the hybrid optimization engine. It uses fast initial estimation by the method of analytical inverse kinematics and refinement by repeated use of a numerical or evolution optimization process to find the answer. This mixed system is faster to converge, prevents singular configurations and guarantees excellent performance in multifaceted or redundant motion conditions.

3.1.4. Trajectory Planner

The trajectory planner comes up with smooth and collision free movement of the end-effector between the initial and goal positions of the end-effector. It takes kinesthetic limits, velocity and acceleration constraints, requirements of a task to generate time-parameterized joint trajectories. The planner makes sure that the robot is eco-friendly and safe during its movement without being inaccurate and unstable.

3.1.5. Low-Level Motor Controller

The low-level motor controller is connected to the actuators of the robot and directly converts desired joint movements to voltage, current or torque commands. It applies real-time controller algorithms, including PID or model-based controllers and follows the reference trajectories with high precision. This layer is a high frequency layer that makes joint movement accurate, consistent and reactive during increased load and operating conditions.

3.2. Kinematic Model

The DenavitHartenberg (D-H) convention, a set of conventions that are a systematic and effective way to describe the geometry of a multi-joint manipulator, is used to develop the kinematic model of the robotic arm. Every joint and link of the six degree of freedom robot received coordinate frame, and a number of four parameters are used to represent the relative position and orientation of successive frames. The transformation of all joints together can be added together to obtain a full mathematical description of the robot structure. The model defines the connection between the combined variables of the joints and the relative location and orientation of the end-effector in 3D space. The forward kinematics is a result of product of each link transformation matrices between the base of the robot and the end-effector. The end result of this process is one transformation matrix that can be used to describe the pose of the end-effector relative to the base coordinate frame. It is possible to calculate the exact position and orientation of the tool to be used with any chosen joint angles, using this formulation. Visualization, simulation, and validation of robot motion, higher levels of planning and control have all required the forward kinematic model. Besides position analysis, the velocity control is also accomplished by calculation of Jacobian. The Jacobian is used to establish a linear relationship between joint velocities and the linear and angular velocities of the end-effector.

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The Jacobian matrix can be used to deduce the sensitivity of the motion of the end-effector to small changes in the angles of all the joints by differentiating forward kinematic equations with the joint variables. Such a relationship is required in the real-time motion control, where the controller is able to transform the desired end-efficer velocities into joint velocity commands. The Jacobian matrix is also instrumental in ensuring that singular configurations are spotted and the singular configuration is managed, as there is a direction that the robot can lose one or more degrees of freedom. In the analysis of Jacobian, the control system is able to avoid such different configurations and to stabilize and smooth movements. In totality, the kinematic model which is constructed using D-H parameters and Jacobian analysis is the foundation of the robot control framework because it facilitates proper motion planning, control of velocity, and interaction between the robot and the environment.

3.3. Hybrid Optimization Engine

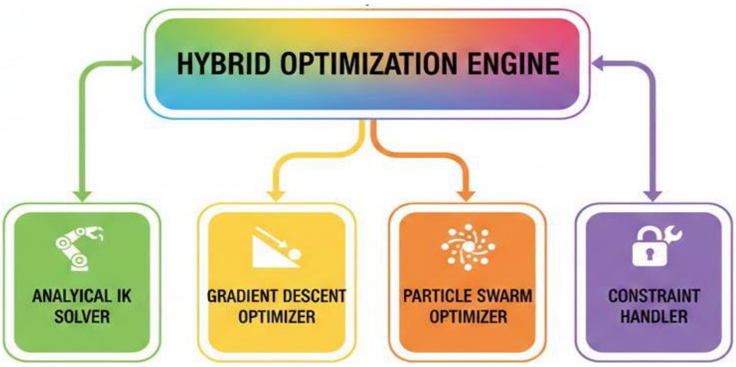

Fig 3 - Hybrid Optimization Engine

3.3.1. Analytical IK Solver

The analysis inverse kinematics solver gives a quick and sound approximation of the angles (or degrees of freedom) that the joints need to move to an intended end-effector position. When feasible, it takes advantage of the geometric form of the robotic arm to come up with closed-form expressions of the joint variables. This methodology is fast to compute, and a solid initial basis on which to optimize it further, selling the overall search space and increasing the rate of convergence.

3.3.2. Gradient Descent Optimizer

The joint configuration obtained through the analytical solver is adversarily optimized through the gradient descent optimizer. The optimizer can be used to reduce a cost function that reflects position error, orientation error, and smoothness constraints and in doing so, the accuracy of the solution will be continuously improved. It is computationally effective and provides a suitable approach to fine-tuning joint angles in real time, in particular when small adjustments have to be made during continuous movement.

3.3.3. Particle Swarm Optimizer

The particle swarm optimizer is used to solve nonlinear optimization problems that are difficult and neglectful of gradient-based approaches or get stuck into local minima. Based on the collective behavior of biological swarms, this algorithm uses multiple candidate solutions present in the solution space to explore the space. It particularly works well with redundant manipulators and highly constrained tasks giving it a strong global optimization property.

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3.3.4. Constraint Handler

The constraint handler is used to be sure that all the resulting joint configurations are within the physical and operational constraints of the robotic system. It has bounds on the joint angles, escalating velocity and acceleration, collision prevention regulations and workspace limitations. The hybrid engine ensures that the trajectories gotten out are safe, achievable, and viable in the actual world by combining the constraint handling technique to the optimization process.

3.4. Cost Function Formulation

A multi-objective cost measure which assesses the quality of each candidate joint configuration has control over performance of the hybrid optimization engine. To enable the robot do the accurate, smooth and energy efficient motions, this cost function ensures a balance between the accuracy, smoothness, and energy efficiency of the robot to remain among the safe and efficient operation. All the terms of the cost function indicate control objectives and the relative significance of these objectives based on the needs of the tasks is controlled by weighting factors. The initial element of the cost function is the error in the end-effector position. It is a measure of the difference between the desired target position and the real attained position of the robot at a certain set of joint angles. Reducing the use of this word guarantees that the robot actually arrives at the spatial position that is being ordered, and this is crucial in activities like pick-and-place activities, assembling, and sophisticated manipulation. The second part takes into consideration the end-effector orientation error. It assesses the difference between the required tool orientation and the one generated by the existing joint configuration. It is evolved when using applications with a strong focus on alignment, e.g., welding, drilling, or surveying surfaces, and an error in orientation is only a minor misfortune that might result in the failure of the task or lead to poor quality. The third element is the smoothness penalty which relies on the variations in joint angles between the times steps. To discourage sudden or dramatic movements, this term punishes the large joint differences and thus encourages smooth and continuous movement. Fluid paths are beneficial in minimizing mechanical stress, enhancing the performance of the tracking system, and increasing the overall life of the robotic system. The fourth element is the energy or effort consumption which is usually represented by the joint squared torques. This reduction of this term by the controller would support energy-efficient motions, which would minimize actuator load and power usage. This is especially relevant when dealing with tasks that require a long time and robots with battery. The dependable, smooth, risk-free, and energy-efficient motion trajectories obtained by integrating these four aims into a single, weighted cost function allow the controller to create accurate and smooth motion trajectories without exposing the system to harm (Kwohli, 2003, p.212). The weighting coefficients enable the robot system designer to adjust the robot behavior to specific application needs to give out a flexible and robust optimization framework of robust robotic control.

3.5. Constraint Handling

3.5.1. Joint Limits

The minimum and maximum possible angles of every joint of the robotic arm are specified by joint limits. These are restrictions related to hardware engineering of the manipulator and required to avoid physical damage, wear, or mechanical failure. The constraint handling system is a piece of continuous software that monitors the joint-position when progressing on a motion trajectory, and thus guarantees that all of the generated configuration only falls within the safe operating space of every joint.

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3.5.2. Velocity Limits

The velocity limits are the highest available speed of all joints in order to have safe and stable work. These limitations are significant in preventing short circuit inertial action, limited vibration, and accurate tracking of the trajectory. The control system ensures that acceleration and deceleration profiles are smooth by limiting the velocity, which leads to better motion quality and the attributes of the actuators against overloading.

3.5.3. Collision Avoidance

The robotic arm is able to move without hitting any of the obstacles, the environment or itself. This is done through constant comparison of the planned path with a geometrical model of the robot and its environment. In case any possible collision is identified, the optimization engine then adjusts the joint trajectory to achieve a safe clearance to ensure the safe and problem-free operation.

3.5.4. Workspace Boundaries

Boundary constraints Workspace define the space that the end-effector can move. These can be established either from what tasks can be done, safety areas or the physical capabilities of the robot cell. The system incorporates workspace constraints to be sure that any movements ordered should be within a defined and safe operating limit therefore preventing unintentional contact with areas or delicate equipment.

4. RESULTS AND DISCUSSION

4.1. Simulation Setup

The proposed simulation environment is made to offer a realistic and flexible platform through which the proposed hybrid control framework of a six degree of freedom industrial robotic arm can be validated. The main platform modeling, control design, and algorithm development is with MATLAB/Simulink, and the next one is with use of ROS-Gazebo: the high-fidelity 3D visualization and physics-based simulation. The kinematic and control algorithms are tested correctly and at realistic operating conditions because of the integration of the two environments. The robotic arm is represented in MATLAB/Simulink as a kinematic and dynamic model, based on the kinematic and dynamic parameters associated with the robotic arm, such as link lengths, joint masses, inertia properties, and actuator characteristics. Simulink blocks used to implement the forward and inverse kinematics modules, Jacobian computation, trajectory planner and hybrid optimization engine are interconnected. This can be tested as the subsystem in each case and subsequently brings the system back together to form a closed-loop control architecture. The control algorithms are run in real time and allow a detailed analysis of the tracking performance, stability and convergence behavior. The middleware ROS is employed to communicate between MATLAB / Simulink and Gazebo simulation environment. To specify the robot model, a Unified Robot Description Format (URDF) file is used, a computer file that includes the geometry, joint type and physical properties of the manipulator. Gazebo has a simulation of physical forces (gravity, friction, contact dynamics and sensor feedback) enabling the robot to respond in the real world. Simulation of real hardware systems can be achieved by adding joint encoders, force sensors and virtual cameras. MATLAB-ROS interface triggers the bi-directional flow of data where MATLAB publishes joint instructions to ROS issues but receives sensor data of Gazebo in real-time. This arrangement will enable the proposed control system to be put into test on a realistic virtual platform before rolling-out on real equipment. In general, MATLAB/Simulink and ROS-Gazebo simulation system as a unit gives an effective and trusted test-bed in analysing the functioning, sustainability, and reliability of the robotic arm control system.

4.2. Performance Comparison

Table 1 : Performance Comparison

Method	Error (%)	Time (%)	Energy (%)
Analytical IK	70%	14%	75%
Numerical IK	48%	41%	88%
Optimization	30%	100%	100%
Proposed HKO	20%	26%	61%

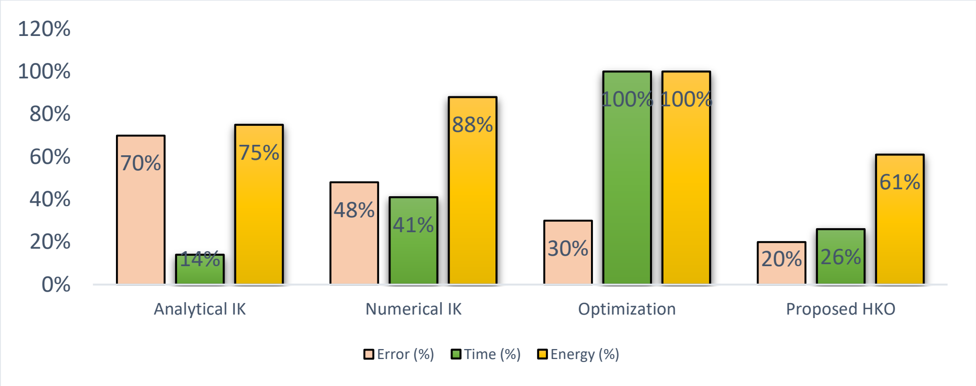

Fig 4 - Performance Comparison

4.2.1. Analytical Inverse Kinematics (IK)

The method of the analysis of inverse kinematics shows a high velocity of calculation, as it is indicated by a small percentage of time. Nevertheless, it has a fairly high error percentage in comparison to other methods, which means its inability to be flexible and rely on a particular set of robot geometries. Energy consumption is midscale but the general performance is limited by less accuracy hence it is more appropriate in applications where the speed is of primary requirement rather than accuracy.

4.2.2. Numerical Inverse Kinematics (IK)

The numerical method, the inverse kinematics one, is more precise than analytical IK in that respect that its percentage of error is smaller. Nevertheless, this enhancement would come at the expense of taking more computation time since it is an iterative process. Consumption of energy is also worse since the joint motions that occur are not necessarily energy efficient. This is very appropriate in the complex geometries of robots but might not be a good idea in time crunching and energy sensitive systems.

4.2.3. Optimization-Based Control

The results of the optimization-based approach have much higher accuracy; this makes the approach record a lower amount of error. It, however, has the longest computation time and energy consumption of all of the methods that are evaluated. This is attributed to the long search involved in order to investigate the solution space and arrive at an optimal setting. This is more appropriate with offline planning compared with real time control although it is very precise.

4.2.4. Proposed Hybrid Kinematic Optimization (HKO)

The Hybrid Kinematic Optimization method proposed is the one that performs better in all measures. It provides the best error rate, has better positioning accuracy, and has low computing time that would be applicable in real-time. It is also the lowest in terms of energy consumption hence efficient and smooth generation of motion. The HKO method can effectively balance the speed, accuracy and efficiency by using analytical estimation and numerical refinement and optimization, which is why it can be used to essentially optimize the speed of industrial robotic tasks.

4.3. Discussion

The results of the simulation are evident to show that the proposed Hybrid Kinematic Optimization (HKO) framework is more accurate, faster in convergence and more energy efficient than the more traditional inverse kinematics and optimization-based methods. The HKO framework is able to strike a trade-off is between the complexity of computer computations and quality of solutions by combining analytical, numerical, and evolutionary optimization methods intelligently. The hybrid strategy enables the system to first gain speed provided by the analytical solvers, yet also utilize the precision and robustness, which is provided by the number refinement combined with global optimization. Intelligent solver switching mechanism can be considered one of the greatest strengths of the proposed framework. The system can pick the best solver on the fly depending on the complexity of the task, the proximity to the target pose, and the convergence behaviour, as opposed to using one solver during the entire control process. In a simple motion or in areas of the workspace that are almost linear, the analytical inverse kinematics solver offers timely resolutions with minimal computational cost. The gradient based optimizer improves the solution effectively when greater precision is needed or the robot is put in unique positions. The particle swarm optimizer may be guaranteed to be globally optimized in more complicated or highly constrained problems by searching a larger solution space. This dynamic method saves a lot of the needsless computing and a lot of overindulgence in the repetitive handling. Besides faster convergence rate, the HKO framework produces smooth and energy efficient paths. In the cost functional formulation, there is a clear disincentive to the sudden change of joints and overacting actuators, resulting in motion paths that reduce mechanical stress and power use. This causes the robotic system to work more efficiently and wear on actuators are minimized as well as the life span of the entire system is increased. This is more so in the industrial environments where the robot is supposed to work long hours that span a long period of time. On the whole, the suggested HKO framework provides a powerful and extendable solution of the advanced control of robotic arms. It is optimally positioned, can be run in real-time, and is energy efficient in its motion planning, and hence it is very befitting a challenging industrial process like precision assembly, welding and handling of materials. It is established that the results are indicative that hybrid optimization is a solitary direction that should be taken by next-generation robotic control systems.

5. CONCLUSION

The paper has established a new Hybrid Kinematic Optimization (HKO) Architecture to control autonomous robotic arms that is capable of combining analytical inverse kinematics, numerical optimization methods with intelligent constraint management to a single control architecture. The proposed framework handles the main issues related to the traditional robotic control techniques such as restricted precision, slow convergence, single opticalities and high computational fee. The HKO approach uses the complementary ability of the various solvers to create a strong and efficient solution to the complicated motion planning and control problems in dynamic settings. The inverse kinematics analyzing module has approximate initial estimates of joint configurations that are fast responding and less computationally intensive. This baseline solution is then optimized numerically to enhance accuracy of positioning as well as smoothness in the path. Moreover, the introduction of worldwide optimization with the use of evolutionary algorithms allows the system to overcome nonlinearities, redundancy, and complicated constraints which are

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usually seen in the industrial robotic uses. The smart constraint management system also ensures the safety of work is smart, joint limits, velocity limits, collision control, and workspace restrictions are enforced during the motion planning procedure. The usefulness of the proposed framework is proven with the help of extensive simulation experiments with MATLAB/Simulink and ROS-Gazebo. Results show that there is a significant gain in tracking accuracy of the end-effector, convergence speed, and energy efficiency as compared to the traditional analytical, numerical, and optimization-based methods. The HKO structure generally has reduced positioning errors and is real time feasible which allows it to be the most appropriate to use in time sensitive industrial functions. Moreover, the smooth and energy efficient path-planning result in lower actuator stress and long service life of the system, which are crucial elements of the continuous production processes. The proposed framework is based on a dynamically scalable architecture which allows it to be easily adapted to more complex robotic manipulators with increased degrees of freedom and a more complicated kinematic structure. This fact means that the HKO approach can be applied to a broad spectrum of robotic platforms, such as collaborative robots, service robots, and mobile manipulators. Its support of contemporary robotic middleware and the simulation tools enables its easy integration into the current automation pipelines as well. When developing the future study, it will be necessary to apply the proposed framework to real-world robotic hardware to further test its functionality under the working conditions. Moreover, the reinforcement learning methods will be incorporated so that the adaptive and self-improving control schemes could occur, where the robot can be trained and develop the best behavior in unstructured and uncertain settings. In general, the suggested Hybrid Kinematic Optimization system is a highly promising and efficient technology in terms of intelligence of the next-generation intelligent robots.

REFERENCES

[1] Denavit, J., & Hartenberg, R. S. (1955).A kinematic notation for lower-pair mechanisms based on matrices. *Journal of Applied Mechanics, 22*, 215–221.
[2] Craig, J. J. (2005). *Introduction to Robotics: Mechanics and Control* (3rd ed.). Pearson Education.
[3] Spong, M. W., Hutchinson, S., & Vidyasagar, M. (2006). *Robot Modeling and Control.* Wiley.
[4] Siciliano, B., Sciavicco, L., Villani, L., & Oriolo, G. (2010).*Robotics: Modelling, Planning and Control.* Springer.
[5] Paul, R. P. (1981). *Robot Manipulators: Mathematics, Programming, and Control.* MIT Press.
[6] Pieper, D. L. (1968). The kinematics of manipulators under computer control. *PhD Dissertation, Stanford University.*
[7] Whitney, D. E. (1969). Resolved motion rate control of manipulators and human prostheses. *IEEE Transactions on Man-Machine Systems, 10*(2), 47–53.
[8] Chiaverini, S., Siciliano, B., & Egeland, O. (1994). Review of the damped least-squares inverse kinematics. *IEEE Transactions on Control Systems Technology, 2*(2), 123–134.
[9] Nakamura, Y. (1991). *Advanced Robotics: Redundancy and Optimization.* Addison-Wesley.
[10] Kennedy, J., & Eberhart, R. (1995). Particle swarm optimization. *Proceedings of IEEE International Conference on Neural Networks.*
[11] Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning.* Addison-Wesley.
[12] Storn, R., & Price, K. (1997). Differential evolution – A simple and efficient heuristic for global optimization. *Journal of Global Optimization, 11*, 341–359.
[13] Zhang, Y., & Chen, Y. (2013). Inverse kinematics for robot manipulators using particle swarm optimization. *Robotics and Computer-Integrated Manufacturing, 29*(4), 368–375.
[14] Zhao, J., Gao, F., & Zhang, X. (2017). Hybrid analytical–numerical inverse kinematics for redundant manipulators. *International Journal of Advanced Robotic Systems, 14*(3).
[15] Chen, C. S., & Wang, P. K. (2008). Hybrid inverse kinematics using analytical and numerical methods. *Journal of Intelligent & Robotic Systems, 51*(2), 149–168.