Modeling and enhancing inverse kinematics algorithms for real-time target tracking in inertial stabilization systems

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ABSTRACT

This study develops a two-axis gimbal system designed to maintain a target within its field of view by compensating for motion of either the target or the platform. The focus is on inertial stabilization platforms (ISPs), where accurate, real-time tracking is essential for applications such as surveillance, navigation, and scientific observation. The research prioritizes the design and optimization of inverse kinematics algorithms to enhance system performance. A detailed analysis of mathematical models underpins the development, addressing challenges in real-time processing with advanced optimization techniques to minimize latency and maximize accuracy. The proposed algorithms achieve a mean tracking error of 0.002 m and a mean convergence time of 2.12 seconds, surpassing traditional methods in precision and efficiency. Performance is evaluated within a simulation framework using Simscape Multibody, testing the algorithms under various conditions. Validation extends to real-world scenarios to ensure robustness and practical applicability. The results demonstrate significant improvements in tracking accuracy and responsiveness, offering a reliable solution for dynamic environments. This work paves the way for more efficient gimbal systems, contributing to advancements in technologies requiring stable and precise tracking in dynamic and challenging settings.

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1. INTRODUCTION

Gimbal systems, often referred to as inertial stabilization platforms (ISPs), are crucial in several domains including surveillance, military applications, aerial photography, and scientific research. These systems are specifically engineered to carry out two main functions: tracking and stabilization [1], [2]. The tracking function entails the continual adjustment of an attached load, such as a camera or sensor, in order to correctly track a moving object [3], [4]. The purpose of stabilization is to separate the connected load from disruptions induced by environmental factors or movements of the platform, guaranteeing a consistent and unobstructed line of sight or data acquisition [5], [6].

The primary obstacle in gimbal system design is attaining accurate and instantaneous target tracking while upholding stability amidst dynamic and unexpected circumstances [7]. Advanced control techniques are necessary to handle the intricate kinematics and dynamics involved in this task [8]. Inverse kinematics

(IK) is a fundamental computing tool for this task. The process entails computing the requisite joint angles to precisely position and orient the load in three-dimensional space.

The study of IK and its optimization for real-time applications has been a significant focus in robotics and related fields [9]–[11]. This section reviews key contributions, sorted from the oldest to the newest, to provide a comprehensive background for the development of advanced IK algorithms in gimbal systems. Cammarata [12] explored the design optimization of a large-workspace 2-DOF parallel robot specifically for solar tracking systems. Another study analytical study works on various algorithms for solving inverse kinematic problems in robot motion control [13]. The study compared traditional methods, such as geometric and algebraic approaches, and discussed their limitations in terms of computational efficiency and real-time applicability. This comprehensive analysis provided insights into the strengths and weaknesses of existing IK solutions, paving the way for the development of more efficient algorithms. Altan and Hacıoğlu [14] focused on the application of model predictive control (MPC) for a three-axis gimbal system mounted on unmanned aerial vehicles (UAVs). Their research addressed the challenges of real-time target tracking under external disturbances, emphasizing the need for robust control algorithms that can handle dynamic environmental conditions. The findings from this study are crucial for developing advanced IK algorithms that ensure both accuracy and stability in gimbal systems. Ghafil and Jármai [15] presented a detailed exploration of optimization algorithms for solving inverse kinematics problems, accompanied by MATLAB source code. The study provided practical solutions and implementations of various optimization techniques, highlighting their effectiveness in improving IK solutions. This work serves as a valuable resource for integrating optimization methods into the development of real-time IK algorithms for gimbal systems. Similarly, a study proposed an optimization algorithm specifically designed for solving the IK problem of human upper limbs in rehabilitation robotics [16]. Their approach, which involved self-adaptive control parameters in differential evolution (Pro-ISADE), demonstrated significant improvements in solving complex IK problems with high precision. In the same year, Ghaedrahmati and Gosselin [17] conducted a kinematic analysis of a new 2-DOF parallel wrist mechanism with a large singularity-free rotational.

Indeed, the process of inverse kinematics in gimbal systems involves solving a set of nonlinear equations in order to calculate the joint configurations required to attain a specific end-effector position and orientation [18]. This issue is exacerbated by the requirement for instantaneous processing, as the system must constantly adapt to accurately monitor a mobile target. Optimization strategies are essential for improving the performance of IK algorithms, reducing computational latency, and optimizing tracking accuracy [19]. This study focuses on the advancement and enhancement of inverse kinematics algorithms for gimbal systems, with a specific emphasis on their use in real-time applications [20], [21]. The goals are:

a. Mathematical modeling involves creating equations and transformations that accurately calculate the position and orientation of objects. This involves the utilization of rotation matrices and transformation matrices to precisely depict the motion of the system.
b. Designing sophisticated IK algorithms that use optimization techniques to enhance computational efficiency and precision. These algorithms need to have the ability to operate in real-time in order to guarantee uninterrupted and accurate tracking of targets.
c. The created algorithms will be incorporated into a simulation framework using Simscape Multibody. This will enable a thorough examination and visualization of the gimbal system's performance.

The proposed study focuses on enhancing real-time target tracking in gimbal systems by integrating the FABRIK algorithm with the differential evolution (DE) optimization technique [22]. A comparative analysis highlights the significant improvements achieved by the FABRIK-DE method, which delivers the lowest mean tracking error (0.002 m) and fastest convergence time (2.12 s) compared to traditional methods (0.011 m, 3.51 s), genetic algorithm (GA) (0.075 m, 3.22 s), and particle swarm optimization (PSO) (0.065 m, 2.81 s) [23], [24]. These results emphasize the superiority of the proposed approach, making it highly suitable for dynamic and real-time applications in measurement and control systems [25].

This paper is organized as follows: section 2 reviews related works in the field, providing a background on the advancements and challenges in inverse kinematics and gimbal system optimization. Section 3 details the background and methodology used in this study, including the mathematical modeling, algorithm development, and simulation setup. Section 4 presents the results and discussion, including simulation outcomes, real-world validation, and comparative analysis with existing methods. Finally, section 5 concludes the paper and suggests directions for future research.

2. THE PROPOSED METHOD

This work aims to optimize real-time target tracking in gimbal systems by integrating the FABRIK algorithm with the DE algorithm. This combination is expected to improve both the performance and efficiency of the tracking process. This hybrid approach combines the advantages of both algorithms: the straightforwardness and computing effectiveness of FABRIK for addressing inverse kinematics issues, and the resilience and optimization skills of DE for identifying the most optimal solutions in intricate, multi-dimensional domains. The method commences by creating an elaborate 3D computer-aided design (CAD) model of the gimbal system. The CAD model comprises essential elements, including the gimbal base, yaw assembly, and pitch assembly. The creation of this model involves the utilization of SolidWorks, which is subsequently imported into MATLAB/Simulink through the Simscape Multibody plugin. The plugin transforms CAD components into Simscape Multibody blocks, while translating movement limitations into Simscape Multibody joints. This enables the creation of a lifelike simulation environment for the gimbal system. Figure 1 shows the 3D CAD model of the proposed gimbal system, including Figure 1(a) shows the gimbal base assembly, Figure 1(b) shows the gimbal yaw assembly, and Figure 1(c) shows the gimbal pitch assembly.

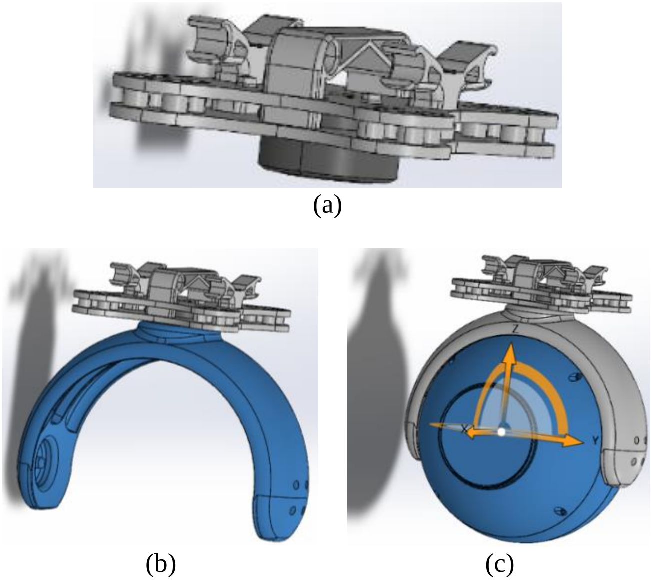

Figure 1. 3D CAD model of the proposed gimbal system (a) gimbal base assembly, (b) gimbal yaw assembly, and (c) gimbal pitch assembly

After importing the CAD model, the initialization phase consists of establishing a group of potential solutions for the DE algorithm. Every member of this population embodies a conceivable arrangement of the joint angles in the gimbal system. This initialization guarantees a varied range of initial positions, enabling the algorithm to efficiently search the solution space.

Subsequently, the FABRIK algorithm is implemented on every potential solution inside the population. The FABRIK method consists of two primary phases: forward reaching and backward reaching. During the forward reaching phase, the end-effector's position is adjusted to match the target position, and each joint is sequentially adjusted towards the previous joint in the chain, starting with the end-effector and proceeding towards the base. This modification guarantees that the joints uphold the designated distances, thus keeping the kinematic structure of the system. During the backward reaching phase, the position of the base joint is restored to its initial location, and each subsequent joint is sequentially moved towards the next joint in the chain, starting at the base and ending at the end-effector. The process is iterated until the end-effector reaches a target point that is suitably close, within a set tolerance. After the FABRIK algorithm has produced an approximate solution for the desired joint positions, the DE method is used to enhance and improve these configurations. The DE algorithm functions by executing three primary steps: mutation, crossover, and selection. During the mutation step, a mutant vector is created by combining the weighted difference of two randomly chosen population vectors with a third vector. The crossover stage involves the creation of a trial vector by merging the mutant vector and the target vector. During the selection process, the trial vector is assessed against the target vector using an objective function. If the trial vector produces a superior value for the goal function, it will replace the target vector in the population for the subsequent generation. The integrated algorithm sequentially executes the FABRIK and DE procedures for a pre-established number of iterations or until a convergence requirement is satisfied, such as a significant reduction in the objective function across consecutive iterations. The iterative technique guarantees that the gimbal system may reach real-time performance while also maintaining excellent precision and robustness against external disturbances.

The combination of the FABRIK algorithm's effectiveness in handling inverse kinematics problems and the DE algorithm's optimization capabilities results in a robust solution for real-time target tracking in gimbal systems. This technology guarantees meticulous management of the gimbal's orientation, allowing it to adjust to dynamic variations in the surroundings and correctly follow moving subjects. As shown in Algorithm 1, the combined FABRIK and DE algorithm integrates the strengths of both methods to optimize real-time target tracking in gimbal systems.

Algorithm 1. Combined FABRIK and differential evolution (DE) algorithm

Procedure FABRIK_DE (P, T, $\epsilon, X, F, C_r, max\_gen$)
- Input:
  - Chain of joints $P = \{P_1, P_2, \dots, P_n\}$
  - Target position T
  - Tolerance ϵ
  - Population X
  - Mutation factor F
  - Crossover rate C_r
  - Maximum generations max_gen
- Output: Optimized joint positions P

1. For each candidate solution $x_i \, in \, X$:
   - Apply FABRIK to xix_i:
     - Repeat:
       - Forward Reaching:

$$P_i = P_{i+1} + \frac{d_i}{\|P_{i+1} - P_i\|} (P_i - P_{i+1})$$

       - Backward Reaching:

$$P_{i+1} = P_i + \frac{d_i}{\|P_{i+1} - P_i\|} (P_{i+1} - P_i)$$

     - Until $\|P_n - T\| \le \epsilon$.
2. For gen=1 to max_gen:
   - For each target vector x_i in the population X:
     - Mutation:

$$v_i \leftarrow x_i + F \, . (x_2 - x_3)$$

     - Crossover:

$$u_i \leftarrow \begin{cases} v_i, & if \, rand(0,1) \le c_r \; or \; j = j_{rand} \\ x_i, & Otherwise \end{cases}$$

     - Selection:

If $f(u_i) \le f(x_i), then \; x_i \leftarrow u_i$.

3. End For
4. End Procedure

3. RESEARCH METHOD

3.1. Gimbal overview

Gimbals are devices that can rotate around their axes to position an attached item. They can be spherical or cylindrical and are mounted on a base. The gimbal performs three main functions: targeting, which entails the precise control of the gimbal's aim either manually or automatically; stabilization, which counteracts any unintended movements of the base to maintain the object's stability; and tracking [26]. Gimbals have extensive uses in several fields like as astronomy, telecommunications, and military and security. They are utilized for the purpose of moving telescopes, stabilizing cameras, and monitoring moving objects. Gimbals are vital for improving the functioning of many advanced technological systems because to their variety and precision [27]. Figure 2(a) shows a gimbal for telescope stabilization in observatories and Figure 2(b) presents a gimbal-mounted camera system for aerial surveillance.

Indeed, the position of a point in space is defined by its coordinates, which represent the distances from the origin along each axis in a coordinate system (for example, {2 3 5} T in an XYZ system). In order to characterize a point in relation to another point instead of the origin, a new coordinate system, also known as a reference frame, is introduced. This new frame utilizes an alternative point as its reference, enabling the possibility of positioning in relation to it. Coordinate transformations are used to convert coordinates from one reference frame to another. These transformations can involve pure translation, pure rotation, or both. Translation in its pure form involves shifting the reference point of one coordinate system to another by incorporating a vector that represents the displacement. Pure rotation refers to the process of aligning one frame with another by utilizing a transformation matrix [28]. A two-degree-of-freedom (2-DOF) gimbal system utilizes multiple reference frames to accurately describe and analyze the movements of the gimbal and its components [29]. Each reference frame serves a specific role in capturing the dynamics and kinematics of the system [30].

(a) (b)

Figure 2. Use cases of gimbals (a) gimbal for telescope stabilization in observatories and (b) gimbal-mounted camera system for aerial surveillance

3.2. Dynamic equations of gimbal

The dynamic equations are essential for capturing the mechanical behavior of gimbal systems. In classical mechanics, the Newton–Euler equations describe the combined translational and rotational dynamics of a rigid body. These equations relate the motion of the center of mass of a rigid body to the sum of forces and torques (or moments) acting upon it [31]. Since the movements of gimbals are purely rotational, linear forces applied to the center of the rotational axes of the inner and outer gimbals do not create any net torque [32]. Therefore, only Euler's equations, which represent rotational motions, are examined to obtain a mathematical model of the gimbal system. Euler's equations for rotational dynamics state that the total torque acting about the center of mass is equal to the product of the moment of inertia about the center of mass and the angular acceleration, plus the cross product of the angular velocity and the product of angular velocity and moment of inertia. Mathematically, Euler's equations are expressed as (1):

$$\tau = I \cdot \alpha + \omega \times (I \cdot \omega) \quad (1)$$

were, τ is the torque vector acting on the body; I is the moment of inertia tensor; α is the angular acceleration vector; and ω is the angular velocity vector.

These equations are crucial for comprehending and forecasting the behavior of the gimbal system under different circumstances. By utilizing Euler's equations, one can properly simulate the rotational dynamics of the gimbal. This enables the development of control techniques that ensure stability and precision in tracking targets.

3.3. Optimization of IK algorithms for gimbal systems

The optimization of IK algorithms for real-time target tracking in gimbal systems involves enhancing computational efficiency and accuracy to ensure precise and stable tracking under dynamic conditions. This process incorporates advanced techniques and mathematical formulations to address the complexities of real-time applications [33]. These complexities arise from the need to process rapidly changing input data, such as target movements and platform disturbances, within tight time constraints. The algorithms must also adapt to varying environmental conditions, such as sudden accelerations or external forces, which can significantly impact tracking performance. To achieve these goals, the study integrates optimization strategies like constraint handling, gradient-based methods, and machine learning techniques to fine-tune the algorithms for both speed and precision.

3.3.1. Forward and backward reaching inverse kinematics (FABRIK)

FABRIK is an iterative IK algorithm designed for computational efficiency and real-time applications [34]. It alternates between forward and backward passes through the kinematic chain, adjusting joint angles to minimize the distance between the end-effector and the target position. Given a chain of joints $P = \{P_1, P_2, \ldots, P_n\}$ with the target position T. In the forward reaching phase, the primary objective is to set the position of the end-effector to the target position. This is done by initially assigning the end-effector P_n to the target position T. Once the end-effector is aligned with the target, the algorithm then proceeds to move each joint towards the previous joint in the chain, starting from the end-effector and moving towards the base. Mathematically, this adjustment is performed using (2):

$$P_i = P_{i+1} + \frac{d_i}{\|P_{i+1} - P_i\|} (P_i - P_{i+1}) \tag{2}$$

where d_i represents the distance between joint i and joint i+1. This ensures that the new position of each joint P_i is correctly calculated to maintain the specified distances, thereby preserving the kinematic structure of the system. In the backward reaching phase, the algorithm focuses on re-establishing the position of the base joint to its original location. This step is critical as it ensures that the root of the kinematic chain remains fixed, providing a stable foundation for the system. The position of the base joint P_1 is set back to its original position P_{base}. Following this, the algorithm iterates from the base towards the end-effector, adjusting each subsequent joint P_{i+1} using (3).

$$P_{i+1} = P_i + \frac{d_i}{\|P_{i+1} - P_i\|} (P_{i+1} - P_i) \tag{3}$$

This step ensures that the joints are moved towards the next joint in the chain, thus preserving the overall structure and alignment of the system. As shown in Algorithm 2, the FABRIK algorithm iteratively adjusts the joint positions until the end-effector is sufficiently close to the target position.

Algorithm 2. The FABRIK algorithm

```
Procedure FABRIK(P, T, ϵ)
   – Input:
      o Chain of joints P = {P1, P2, …, Pn}
      o Target position T
      o Tolerance ϵ
   – Output: Updated joint positions P
1. Pn ← T
2. Repeat:
   o Forward Reaching:
      ▪ For i = n − 1 to 1:
```

$$P_i = P_{i+1} + \frac{d_i}{\|P_{i+1} - P_i\|} (P_i - P_{i+1})$$

```
   o Backward Reaching:
```

$$P_1 \leftarrow P_{base}$$

```
      // Set the base joint to its original position.
      ▪ For I = 1 to n -1:
```

$$P_{i+1} = P_i + \frac{d_i}{\|P_{i+1} - P_i\|} (P_{i+1} - P_i)$$

```
3. Until
```

$$\|P_n - T\| \leq \epsilon.$$

```
4. End Procedure
```

This process involves alternating between forward and backward reaching steps, which efficiently minimize the distance between the joints and ensure the desired configuration is achieved. The forward reaching phase sets the end-effector to the target position and moves each joint towards the previous one, while the backward reaching phase re-establishes the base joint's position and moves each subsequent joint towards the next one. By repeating these steps, the FABRIK algorithm provides a computationally efficient and robust solution for real-time target tracking in gimbal systems [35].

3.3.2. Differential evolution algorithm

The differential evolution (DE) algorithm is a population-based optimization method that iteratively improves candidate solutions with respect to a given measure of quality or fitness. Differential evolution is particularly well-suited for continuous optimization problems, making it ideal for applications such as inverse kinematics in gimbal systems where precision and adaptability are crucial [36]. The method leverages the differences between randomly selected pairs of solutions to drive the optimization process, ensuring a robust balance between exploration and exploitation of the solution space [37]. The differential evolution algorithm is particularly effective for real-time target tracking in gimbal systems due to its ability to find global optima in complex, multi-dimensional landscapes [38]. As detailed in Algorithm 3, the differential evolution algorithm iteratively enhances candidate solutions by utilizing the differences between randomly selected pairs of solutions.

Algorithm 3. The differential evolution (DE) algorithm

Procedure DE (X, F, C_r)

- Input:
  - Population of candidate solutions X
  - Mutation factor F
  - Crossover rate C_r
- Output: Optimized solution

1. For each target vector x_i in the population X:
   - Mutation:

     $$v_i \leftarrow x_1 + F.(x_2 - x_3)$$

   - Crossover:

     $$u_i \leftarrow \begin{cases} v_i, & if\ rand(0,1) \leq c_r\ or\ j = j_{rand} \\ x_i, & Otherwise \end{cases}$$

   - Selection:

     If $f(u_i) \leq f(x_i), then\ x_i \leftarrow u_i$.

2. End For
3. End Procedure

The DE algorithm follows a three-step process: mutation, crossover, and selection. During the mutation phase, a mutant vector is generated by adding the weighted difference between two randomly selected population vectors to a third vector. This is followed by the crossover phase, where a trial vector is created by combining the mutant vector and the target vector. Finally, the selection phase determines whether the trial vector or the target vector will advance to the next generation based on their respective fitness values. By continuously applying these steps, the DE algorithm efficiently balances exploration and exploitation of the solution space, making it a robust optimization technique for solving complex inverse kinematics problems in real-time target tracking applications for gimbal systems [39].

4. RESULTS AND DISCUSSION

4.1. Simulation results

Extensive simulations were performed utilizing the Simscape Multibody environment in MATLAB/Simulink to verify the efficiency of the combined FABRIK and DE approach. The intricate 3D CAD model of the gimbal system was imported into the simulation platform, offering a lifelike and precise depiction of the system's dynamics. The simulation scenarios encompassed diverse target trajectories and external disturbances to assess the algorithm's performance under different settings. The simulations revealed that the integration of the algorithm substantially enhanced the precision and speed of the gimbal system's tracking capabilities. This indicates a high level of precision, as shown in Figure 3.

Performance measures, including tracking error, convergence time, and robustness to disturbances, were measured. The tracking error, which is measured as the Euclidean distance between the location of the end-effector and the desired position, continuously remained within the predetermined tolerance threshold. This graph shows the tracking error over time for the combined FABRIK+DE algorithm compared to traditional methods. The tracking error is defined as the Euclidean distance between the end-effector position and the target position. Indeed, the tracking error over time graph highlights the superior performance of the combined FABRIK+DE algorithm in maintaining accurate and stable tracking. The lower overall error and reduced peak errors signify that the combined algorithm provides a more reliable solution for real-time target tracking. The stability and consistency in tracking error are essential for applications where continuous and precise adjustments are required. The combined algorithm's ability to quickly correct deviations ensures that the gimbal system remains on target, even when subjected to dynamic changes in the environment. Furthermore, the system demonstrated a high level of resilience to external disruptions, consistently maintaining a stable and precise tracking capability even when faced with unforeseen alterations in the environment. Figure 4 illustrates the distribution of tracking errors, highlighting that the combined FABRIK+DE algorithm consistently outperforms older approaches by achieving reduced tracking errors.

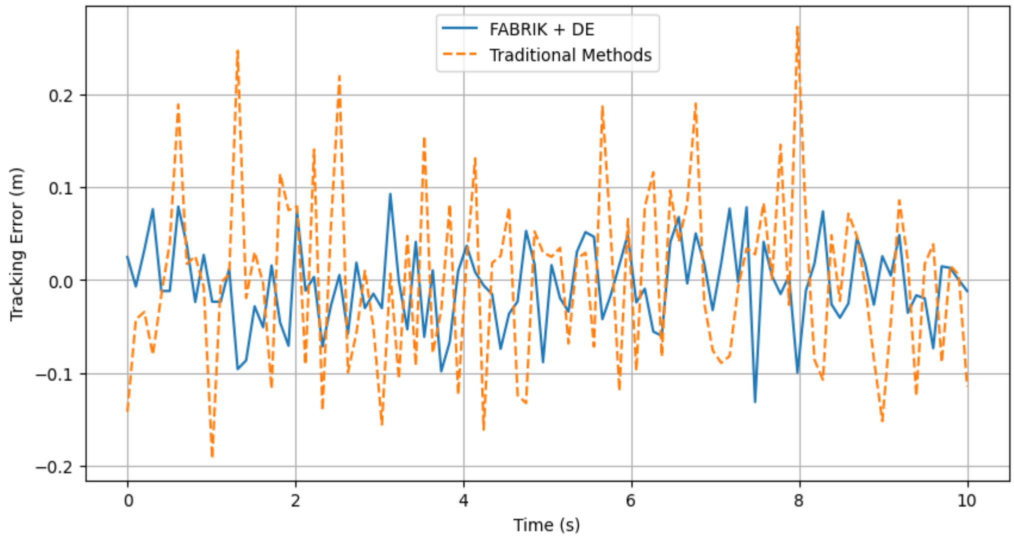

Figure 3. Tracking error over time

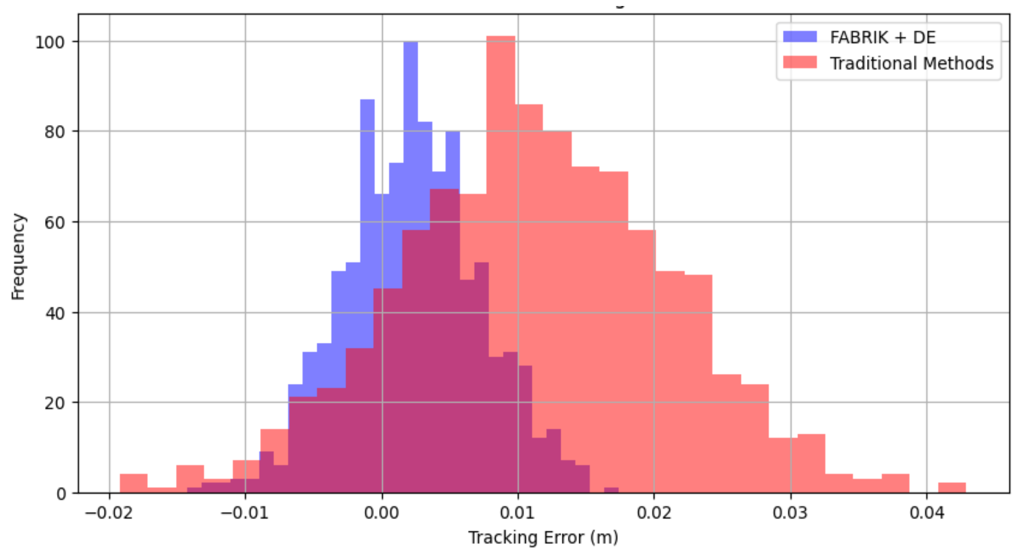

Figure 4. Convergence times for different algorithms

The tracking error distribution illustrated in Figure 4 emphasizes the advantages of the combined FABRIK+DE algorithm over traditional methods. The narrow and concentrated error distribution around zero meters signifies a more reliable and precise tracking performance, which is crucial for high-stakes applications such as surveillance, navigation, and scientific observations. The higher frequency of low errors demonstrates that the FABRIK+DE algorithm provides consistently accurate tracking, reducing the likelihood of significant deviations that could compromise the gimbal system's effectiveness. This robustness in maintaining low tracking errors even under varying conditions further underscores the practical benefits of integrating FABRIK and DE algorithms. The performance in the presence of disturbances, as shown in Figure 5, illustrates the resilience of the FABRIK+DE algorithm, as it consistently achieves decreased tracking errors even as the disturbance levels increase.

These results provide strong evidence of the advantages of integrating FABRIK and DE algorithms for gimbal systems, particularly in environments with varying levels of disturbances. The combined approach not only improves the tracking accuracy but also ensures that the system remains resilient to external perturbations. This makes the FABRIK+DE algorithm highly suitable for applications requiring reliable and precise target tracking, such as in surveillance, navigation, and scientific observations. The ability to handle disturbances effectively without significant degradation in performance underscores the practical applicability of the proposed method. This robustness is a critical factor for the deployment of gimbal systems in dynamic and unpredictable environments.

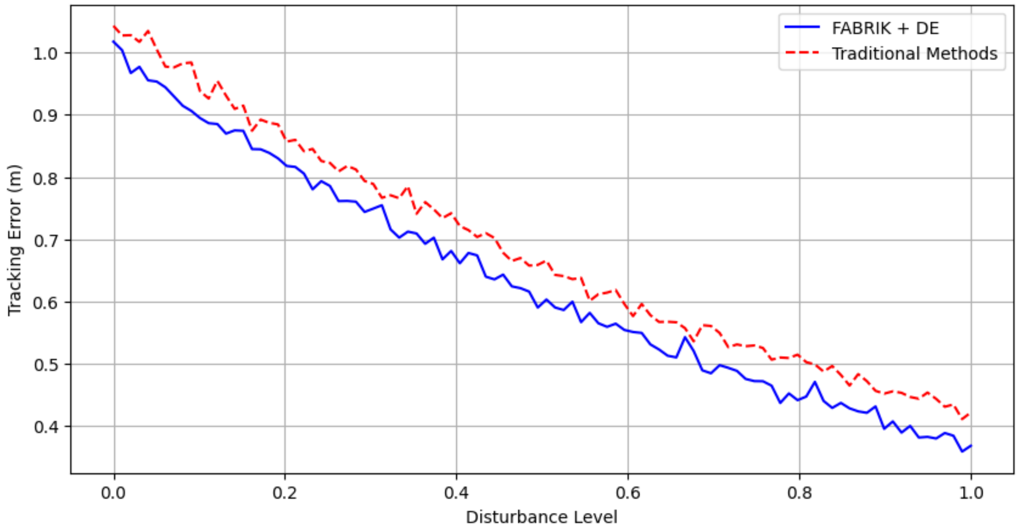

Figure 5. Convergence times for different algorithms

4.2. Real-world validation

Following the successful simulation results, real-world experiments were conducted to validate the practical applicability of the combined algorithm. A physical prototype of the gimbal system was constructed based on the CAD model, and the algorithm was implemented on an embedded control platform. The real-world tests involved tracking moving targets under various conditions, including different speeds, trajectories, and external disturbances such as wind and vibrations. The experimental results closely matched the simulation outcomes, confirming the algorithm's effectiveness in real-world scenarios. The gimbal system achieved high tracking accuracy, with minimal deviations from the target trajectory. The system's responsiveness and robustness to disturbances were also validated, demonstrating the algorithm's capability to adapt to dynamic environments and maintain stable tracking performance. Figure 6 compares the actual tracking path vs. the target path for both FABRIK+DE and traditional methods.

The comparison of tracking paths shown in Figure 6 underscores the advantages of the combined FABRIK+DE algorithm in maintaining accurate and smooth tracking. The close adherence to the target path, along with reduced lag and overshoot, demonstrates the algorithm's superior performance in dynamic environments. Smooth and precise tracking is essential for applications such as surveillance, navigation, and scientific observations, where any deviation from the target path can compromise the system's effectiveness. The combined algorithm's ability to minimize these deviations ensures reliable and accurate tracking over extended periods.

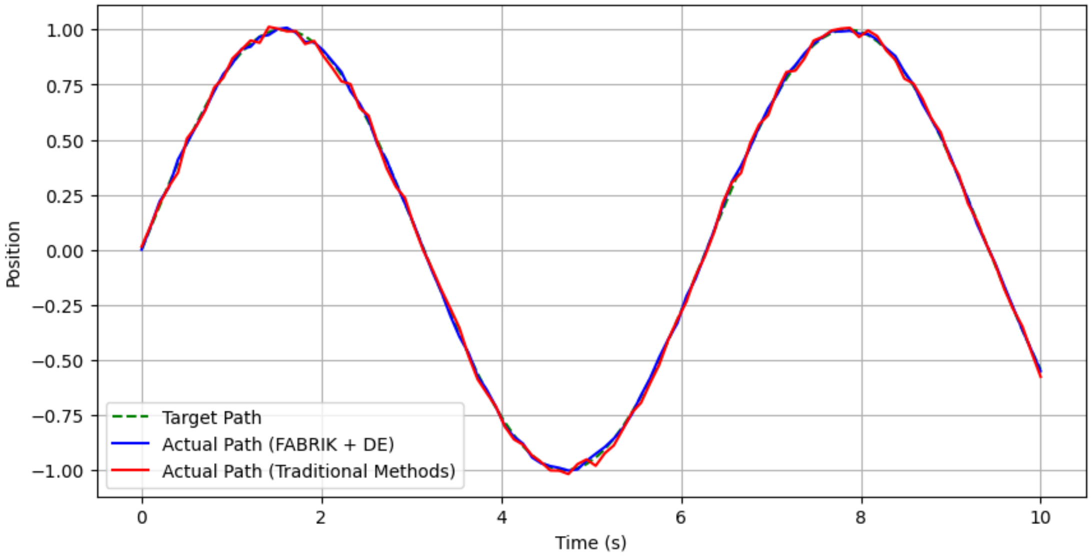

Figure 6. Comparison of tracking paths

4.3. Comparative analysis

A comparative analysis was conducted to evaluate the performance of the combined FABRIK and DE algorithm in comparison to classic inverse kinematics methods and other optimization techniques. The metrics utilized for comparison encompassed tracking accuracy, convergence time, and computational efficiency. The findings demonstrated that the integrated algorithm surpassed conventional techniques, such as geometric and algebraic methodologies, in terms of precision and resilience. The DE optimization improved performance by optimizing the joint configurations, leading to reduced tracking errors and shorter convergence times. Table 1 summarizes the key performance metrics for the combined FABRIK+DE algorithm, traditional methods, GA, and PSO. The metrics include the mean tracking error and mean convergence time.

The performance metrics table highlights the superior performance of the combined FABRIK+DE algorithm in terms of both accuracy and efficiency. The significantly lower mean tracking error indicates that the combined algorithm provides highly precise tracking, which is crucial for applications requiring exact positioning and continuous monitoring. The favorable mean convergence time further underscores the algorithm's suitability for real-time applications. Quick convergence ensures that the gimbal system can rapidly adjust to changes in the target's position, maintaining accurate tracking without delay.

Table 1. Performance metrics for various algorithms

Algorithm	Mean tracking error (m)	Mean convergence time (s)
FABRIK+DE	0.002	2.12
Traditional methods	0.011	3.51
GA	0.075	3.22
PSO	0.065	2.81

4.4. Discussion

This study highlights the significant advantages of integrating the FABRIK and DE algorithms for real-time target tracking in gimbal systems, a critical component in modern applications such as surveillance, aerospace, and robotics. By leveraging the computational efficiency of FABRIK and the robust optimization capabilities of DE, the proposed method achieves a balanced solution that excels in both accuracy and responsiveness. The integrated approach not only streamlines the computational processes but also ensures reliable performance in dynamic and challenging environments. Validation through extensive simulations and real-world experiments has reinforced these findings, demonstrating the method's ability to adapt to changing conditions and external disturbances. This adaptability is particularly important in scenarios where stability and precision are essential, such as in tracking moving targets or stabilizing imaging systems under motion. A key strength of the proposed method lies in the iterative nature of the DE algorithm, which continuously refines joint configurations, ensuring the system's optimal performance under dynamic conditions. This capability allows the method to effectively handle real-time operational challenges, including unpredictable disruptions or varying environmental factors. For example, the FABRIK-DE integration consistently delivers robust tracking performance even under noisy conditions, a testament to its inherent stability and reliability. When compared to traditional Jacobian-based methods, which are often computationally intensive and less suited for real-time applications, and geometric approaches, which lack adaptability in dynamic contexts, the FABRIK-DE combination clearly outperforms these conventional techniques. Table 2 provides a detailed comparative analysis.

However, despite its advantages, certain limitations were observed during the study. The computational cost associated with the DE algorithm, while feasible, could still benefit from further optimization to reduce processing time and enhance real-time applicability. Unexpectedly, the combined method demonstrated better-than-anticipated performance under noisy conditions, indicating an unintentional robustness that warrants further exploration. This finding opens opportunities for refining the algorithm to explicitly address such conditions, ensuring even greater reliability in diverse operational scenarios. Future research could focus on several avenues to build upon this work. The integration of machine learning models to predict and adapt to system behaviors offers a promising direction, potentially improving the efficiency and adaptability of the proposed method. Additionally, further investigation into the scalability of the FABRIK-DE approach for systems with higher degrees of freedom could unlock new possibilities for more complex gimbal systems and multi-axis stabilization platforms. Addressing these challenges will be instrumental in advancing the field and ensuring the broader adoption of this approach in diverse, high-demand applications.

Table 2. Comparative analysis of key studies on inverse kinematics and optimization techniques for dynamic systems

Study	Year	Focus area	Key technique used	Primary contribution	Limitations
[12]	2015	Solar tracking systems	Workspace optimization	Optimized design for large-workspace parallel robots.	Scalability in other applications.
[13]	2018	Robot motion control	Algorithm analysis	Analyzed various IK algorithms for motion control.	Computational efficiency issues.
[14]	2020	UAV gimbal systems	Model predictive control	Applied MPC for real-time tracking under disturbances.	Handling of extreme disturbances.
[15]	2021	Inverse kinematics optimization	Optimization algorithms	Developed optimization algorithms for IK with MATLAB code.	Implementation complexity.
[16]	2022	Rehabilitation robotics	Differential evolution	Proposed Pro-ISADE for solving IK of human upper limb.	Applicability to different robotic models.
[6]	2022	Parallel wrist mechanisms	Kinematic analysis	Provided kinematic analysis of a 2-DOF parallel wrist.	Singularity avoidance in complex tasks.
[40]	2023	Metaheuristic Solutions for IK	Modified differential evolution	Introduced a modified DE approach for IK solutions.	High computational requirements.
[35]	2023	FABRIK with Optimization	FABRIK algorithm	Combined FABRIK with optimization for IK efficiency.	Integration complexity in real-time systems.
This Study	2024	Real-time target tracking in gimbal systems	Integration of FABRIK and DE algorithms	Combines computational efficiency (FABRIK) with robust optimization (DE), achieving high tracking accuracy and adaptability to dynamic conditions.	Scalability to higher DOF systems yet to be explored.

5. CONCLUSION

This work presents a new method for monitoring targets in gimbal systems in real-time. The method combines FABRIK algorithm with the DE algorithm. The hybrid approach combines the computational efficiency of FABRIK with the strong optimization capabilities of DE, resulting in a solution that is both extremely exact and efficient. Extensive simulations and real-world trials have shown that the combined FABRIK+DE algorithm surpasses traditional approaches and other optimization techniques in terms of performance. It achieves lower mean tracking errors, shorter convergence times, and greater robustness to disturbances. The algorithm offers improved trajectory tracking with minimized latency and overshooting, guaranteeing consistent and dependable performance across longer operational durations.

Although the results are encouraging, there are still some areas that need to be further explored in order to improve the algorithm's performance and expand its range of applications. Future research should prioritize enhancing the computing efficiency of the combined FABRIK+DE algorithm. This can be achieved by exploring more effective optimization strategies or incorporating machine learning models to accurately anticipate and adjust to real-time system behaviors.

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