Optimized Kalman filtering in dynamical environments for thumb robot motion estimation

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ABSTRACT

Stroke, a prevalent nerve disorder in Indonesia, necessitates post-stroke rehabilitation like physical and occupational therapy. Hand and finger muscle training, crucial for restoring movement, often involves innovative solutions like finger prosthetic robotics arms. In particular, the advancement in thumb robotics emphasizes the estimation of thumb motion, where the ensemble Kalman filter square root (EnKF-SR) and H-infinity methods are deemed dependable for both linear and nonlinear models. Simulation results, using 400 ensembles, demonstrated nearly identical accuracy between the methods, exceeding 99%, with a 6-7% increase in accuracy compared to 200 ensembles. These advancements offer promising prospects for effective post-stroke rehabilitation and improved thumb movement restoration.

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1. INTRODUCTION

Post-stroke individuals encounter a spectrum of challenges, with only a minor fraction capable of fully restoring their physical capacities [1]–[3]. Roughly 10% of this demographic can reintegrate into the workforce devoid of any residual weakness, while 40% are mildly disabled, and 50% experience severe disabilities. As a result, post-stroke patients often require rehabilitation programs to aid their recovery [4], [5]. Biomedical robotics, particularly assistive technologies like the assistive finger arm robot, play a critical role in this process. These technologies are designed to assist patients, especially those with specific hand and finger movement impairments, in their rehabilitation journey.

However, understanding the biomechanics of the human hand, a complex structure, is essential for effective rehabilitation. Biomechanical research in this field requires precise kinematic data from various hand movements [6]–[9]. Common methods for tracking finger motion include wearable gloves, hand pose estimation through cameras, and electromyography (EMG) [10]. Yet, wearable gloves are highly dependent on individual finger sizes, while computer vision can face obstacles such as occlusions. EMG, although effective, may not provide the desired comfort for stroke patients during their rehabilitation [11].

An alternative solution for estimating finger joint locations is the use of the Kalman filter [12]. Currently, more advanced methods like the H-infinity [13], [14] and ensemble Kalman filter [15], [16] techniques are gaining popularity due to their superior performance compared to the traditional Kalman filter. To better understand and predict the extent of movement limitations in stroke patients, this research incorporates a simulation using a robotic hand. This robotic hand is designed to mimic the symptoms experienced by stroke patients. The hope is that through precise calculations and simulations, researchers can gain valuable insights into the movement limitations and devise more effective rehabilitation strategies for individuals suffering from stroke-induced hemiparesis.

2. RESEARCH METHOD

2.1. Thumb robot

The depiction of the thumb robot's motion through mathematical modeling, as shown in Figure 1, encompasses static equations from (1) to (7), which delineate the simulation system for the robotic hand [17]–[20]. The subsequent section presents the kinematic motion system model of the thumb robot [21].

$$F(X) = f_1 + f_2 + f_3 \tag{1}$$

with,

$$f_1 = \sum_{j=2}^{6} \left(\left(a_{2j} - a_{1j}\right)^T \left(a_{2j} - a_{1j}\right) - (a_{21} - a_{11})^T (a_{21} - a_{11}) \right)^2 \tag{2}$$

$$f_2 = \sum_{j=2}^{6} \left(\left(b_{2j} - b_{1j}\right)^T \left(b_{2j} - b_{1j}\right) - (b_{21} - b_{11})^T (b_{21} - b_{11}) \right)^2 \tag{3}$$

$$f_3 = \sum_{j=2}^{6} \left(\left(c_{2j} - c_{1j}\right)^T \left(c_{2j} - c_{1j}\right) - (c_{21} - c_{11})^T (c_{21} - c_{11}) \right)^2 \tag{4}$$

with,

$$\left(a_{2j} - a_{1j}\right)^T \left(a_{2j} - a_{1j}\right) = (a_{21} - a_{11})^T (a_{21} - a_{11}) \tag{5}$$

$$\left(b_{2j} - b_{1j}\right)^T \left(b_{2j} - b_{1j}\right) = (b_{21} - b_{11})^T (b_{21} - b_{11}) \tag{6}$$

$$\left(c_{2j} - c_{1j}\right)^T \left(c_{2j} - c_{1j}\right) = (c_{21} - c_{11})^T (c_{21} - c_{11}) \tag{7}$$

2.2. Algorithm of H-Infinity

The H-Infinity method stands as an advanced control theory methodology utilized in engineering, particularly focusing on controller design for systems encountering uncertainties and disturbances. Illustrated in Figure 2 is the operational flow of the H-Infinity method. It commences with system modeling and performance specification, aiming to minimize the effects of uncertainties while fulfilling control objectives [22]–[24]. The H-Infinity method is utilized to optimize controller design, which is subsequently scrutinized for sensitivity and implemented into the actual system. Post-implementation, the performance of the closed-loop system is assessed, and iterative design iterations may be required to meet the desired performance and robustness criteria. This algorithm offers a harmonious blend of performance optimization and robustness, finding applications in aerospace, automotive, robotics, and process control for achieving precise and resilient control of intricate systems. Below delineates the stages of implementing the ensemble Kalman filter square root (EnKF-SR) algorithm on the Thumb robot model.

2.3. Ensemble Kalman filter square root method

The EnKF-SR method is an advanced data assimilation technique used in various applications such as weather forecasting and oceanography. Figure 3 illustrates the workflow of the EnKF-SR. It starts with an ensemble of state vectors, advances them in time through a forecast step, and then applies stochastic rescaling to address ensemble under-dispersion. Next, it incorporates observational data by comparing the forecasted ensemble to observations and updates the ensemble to better match the data, while simultaneously adjusting the ensemble's spread. This process is iterated over multiple cycles, yielding an improved estimate of the system state and its associated uncertainty, making the EnKF-SR a powerful tool for assimilating observations into numerical models [25], [26]. The following are the implementation stages of the EnKF-SR on the model of Thumb robot.

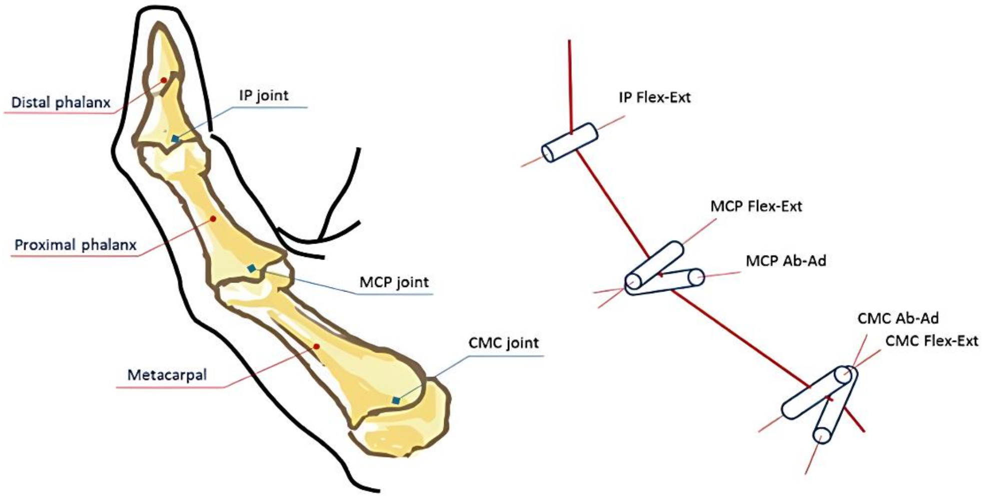


Figure 1. Structure of the thumb and its kinematic model

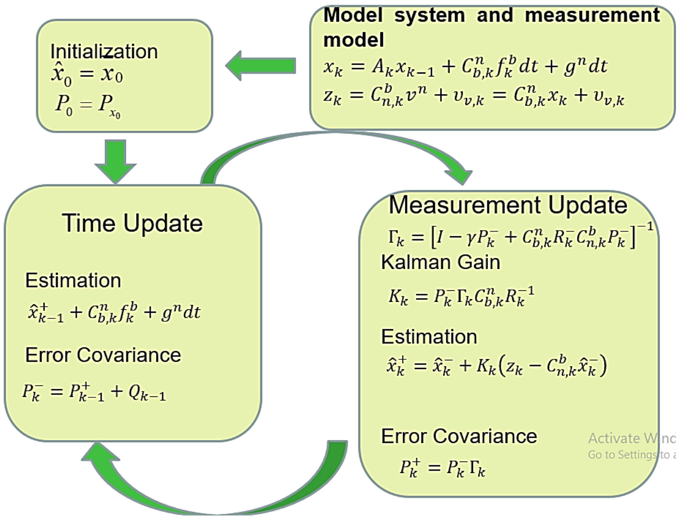


Figure 2. The flow of the H-Infinity method

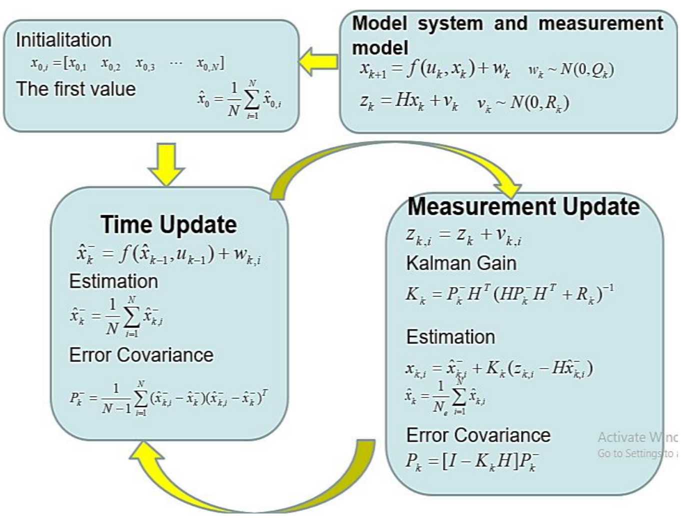


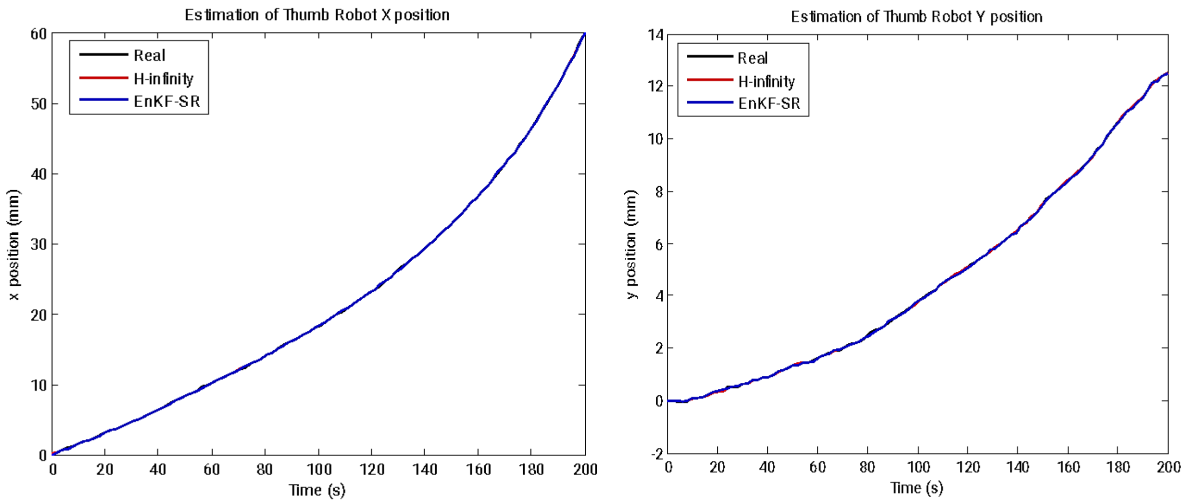
Figure 3. The flow of the EnKF-SR

3. RESULTS AND DISCUSSION

A critical aspect in the advancement of thumb robots lies in accurately estimating their motion, given the pivotal role of the thumb among the five fingers. This research employed the EnKF-SR and H-infinity methods for simulation purposes. Both EnKF-SR and H-infinity are renowned for their reliability in estimating motion across nonlinear and linear models. The primary aim of this research was to develop models and conduct numerical computations for motion estimation and motion control systems, covering nonlinear, linear, dynamic, and kinematic models of thumb robots.

In this research, the research compared the accuracy levels achieved through numerical simulations utilizing the EnKF-SR and H-infinity. This comparison involved evaluating two sets of computational results: one generated from 200 ensembles and the other from 400 ensembles. The simulations focused on the movement of the thumb robot, specifically a semicircular trajectory, facilitating optimal motion of all finger joints within a diameter ranging from approximately 6 to 6.4 cm. This approach aimed at optimizing physical exercise for the thumb. The simulation outcomes, illustrated in Figures 4 and 5, display the results of the H-infinity and EnKF-SR thumb robot simulations.

In Figure 4(a), the estimated position of the thumb robot along the X-axis is depicted, showcasing relatively linear movement. Conversely, Figure 4(b) illustrates the estimation of the thumb robot's position along the Y-axis, displaying less linear movement during the experiment. Moving on to Figure 5(a), the outcomes of employing the EnKF-SR and H-infinity for thumb robot motion estimation are presented, compared to ground truth data using 400 ensembles. Meanwhile, Figure 5(b) showcases the results utilizing 200 ensembles. From these figures, it becomes apparent that both the EnKF-SR and H-infinity exhibit minimal and insignificant differences in thumb robot motion estimation.

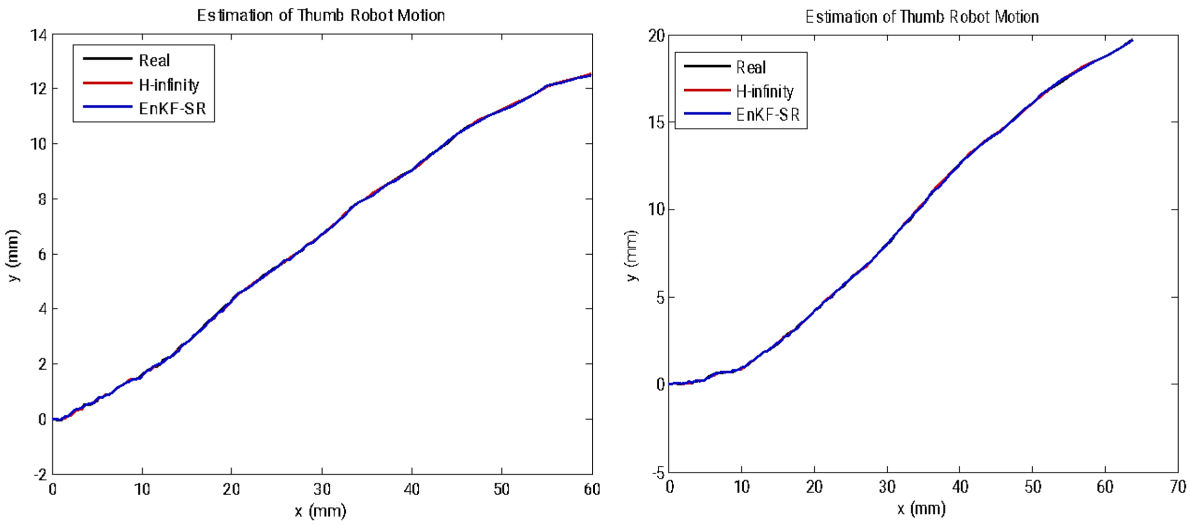


(a) (b)

Figure 4. The results of the application of the EnKF-SR and H-inifnity for thumb robot position estimation using 400 Ensembles in (a) X-plane and (b) Y-plane

Figure 4 illustrates the simulation outcomes regarding the estimation of the thumb robot's motion resembling a semicircle. This was achieved by generating 400 ensembles with 200 iterations. Meanwhile, Figure 5 depicts the simulation using 400 ensembles and 200 iterations. The primary aim of this research is to evaluate the performance of these two approaches by contrasting the numerical computational outcomes under two distinct ensemble conditions: utilizing 200 and 400 ensembles. In Figure 4, the numerical simulation results portray the motion of the thumb in a 2-dimensional space encompassing the X and Y planes, with a duration of 200 seconds. This motion conforms to the mathematical model described for the finger-arm robot above. It is evident from Figure 4 that both the EnKF-SR and H-infinity exhibit nearly identical high accuracy levels, with an error margin of approximately 1%. Moving on to Figure 5, the simulation results were generated using the EnKF-SR and H-infinity, with 200 iterations and 400 ensembles employed. In the EnKF-SR, a semicircular motion with a diameter of 6.128 cm is demonstrated, achieving an overall accuracy rate of 100% within a diameter range of approximately 6 to 6.4 cm. Similarly, employing the H-infinity method yields a motion with a diameter of 6.118 cm, also resulting in a 100% accuracy level within the same diameter range of about 6 to 6.4 cm.

Figure 5(b) displays the simulation outcomes employing 200 iterations and 200 ensembles, utilizing both the EnKF-SR and H-infinity. The EnKF-SR method generates a semicircular motion with a diameter of 6.8 cm, resulting in an overall error of roughly 6.25% within a diameter range of approximately 6 to 6.4 cm. This translates to an accuracy level of 93.75%. On the other hand, the H-infinity method produces a motion with a diameter of 6.896 cm, leading to an error of about 7.75% within the same diameter range. The accuracy achieved with the H-infinity method is 92.25%.



(a) (b)

Figure 5. The results of the application of the EnKF-SR and H-infinity for the thumb robot motion estimation using (a) 400 ensemble and (b) 200 ensemble in XY-plane

Table 1 indicates that the EnKF-SR outperforms the H-infinity in terms of accuracy when tracking the movement of the thumb robot in the XY plane. The difference in accuracy between the two methods is approximately 1.5%. However, it's worth noting that the H-infinity excels in terms of simulation time, being notably faster. Moving on to Table 2, the EnKF-SR demonstrates superior accuracy compared to the H-infinity approach. It achieves accuracy levels exceeding 93% when simulating with 200 ensembles. Notably, when comparing the number of ensembles, both methods achieve 100% accuracy with 400 ensembles. This indicates that while the error is more significant with 200 ensembles, the results are highly reliable for estimating the motion of the thumb robot. Overall, both methods with an accuracy above 93% can be considered reliable for estimating the motion of the thumb robot and can also be applied to estimating the motion of the assistive finger arm robot.

Table 1. Initial value of thumb robot

Var	Initial value	Var	Initial value
a_{11_x}	-3	b_{21_y}	0
a_{11_z}	10	b_{21_z}	48
a_{21_x}	10	c_{11_x}	12
a_{21_z}	42	c_{11_y}	0
b_{11_x}	8	c_{11_z}	42
b_{11_y}	2	c_{21_x}	13
b_{11_z}	-5	c_{21_y}	-3

Table 2. The precision of thumb estimation utilizing the H-infinity and EnKF-SR methodologies employing ensembles of 200 and 400 members

Parameter	EnKF-SR (200 Ensembles)	H-infinity	EnKF-SR (400 Ensembles)	H-infinity
XY motion (%)	93.75	92.25	100	100
Time simulation (s)	11.25	9.8	16.22	13.53

4. CONCLUSION

In conclusion, this study centered on the evaluation of thumb robotic motion utilizing the H-infinity and EnKF-SR method. The study aimed to assess the accuracy of these methods under different ensemble conditions and their performance in tracking the thumb robot's movement. The outcomes of the simulations unveiled that both the EnKF-SR and H-infinity showcased remarkable precision in the estimation of the thumb robot's motion within a 2-dimensional framework. The error for both methods was around 1% when using 400 ensembles, indicating their reliability in accurately tracking the thumb's movement. However, when using 200 ensembles, the EnKF-SR method outperformed the H-infinity method, achieving an accuracy of 93.75% compared to 92.25%. Furthermore, it's important to note that the H-infinity method excelled in terms of simulation time, being notably faster than the EnKF-SR method. The EnKF-SR required more time for simulations but provided higher accuracy. In summary, both the EnKF-SR and H-infinity are reliable for estimating the motion of the thumb robot, especially when using 400 ensembles. The choice between these methods should consider the trade-off between accuracy and simulation time. These findings have significant implications for the development of assistive technologies and rehabilitation strategies, potentially benefiting individuals with hand and finger movement impairments, including those with stroke-induced hemiparesis.

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