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Square Root Ensemble Kalman Filter for Forefinger Motion Estimation as Post-Stroke Patients' Medical Rehabilitation

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Abstract: Hemiparesis is a medical term to describe a condition of weakness on one side of the body or the inability to move a limb on one side. The term comes from the word 'hemi' meaning half or one side and "paresis" meaning weakness. Hemiparesis patients are still able to move the affected side of the body and are not completely paralyzed. It is just that the side of the body experiencing the disorder is so weak and powerless, the movements that arise are also very little. Current robotics technology has developed rapidly along with advances in science and technology to assist medical rehabilitation, one of which is a post-stroke rehabilitation, especially the rehabilitation of finger movement. One technology useful to develop is the finger motion estimation of the Finger Prosthetic Robotic Arm for patients with upper extremity paresis. Finger motion estimation is one of the important aspects in the development of such technology because it is designed to determine the accuracy and effectiveness of the robot in providing motion assistance to hands affected by paresis. The study in this paper used the Square Root Kalman Filter method to estimate the motion of the index finger robot by generating 250 ensembles, 500 ensembles and 750 ensembles. The simulation results with 750 ensembles have the best accuracy of around 97-98%.

Keywords: *hemiparesis, finger prosthetic robotic arm; EnKF; SR-EnKF; forefinger motion estimation.*

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1 Introduction

According to the data from the World Health Organization (WHO), in 2016, the recorded stroke cases ranked second as a non-communicable disease that causes death and third as the main cause of disability worldwide. A stroke can cause weakness in one part or side of the body (hemiparesis), and stroke patients will have difficulty moving and using one side of their body. The affected limbs are usually the facial muscles, respiratory muscles of the chest, arms, hands, or lower limbs on one side. It can occur on the right or left side only and if it occurs on both sides, it is called total or bilateral paresis [1].

Stroke is the medical term for a condition under which blood cannot flow to the brain normally due to the blockage (Ischemic Stroke) or rupture of blood vessels (Hemorrhagic Stroke). A stroke can cause disability on one side of the body, including the upper limbs such as fingers being difficult to move. So, rehabilitation is needed to restore the function of the fingers [2]. Hands and fingers are the most important and complex parts of the human. The muscles in them can perform any movement as the human brain commands, without having to control them one by one.

Robotics technology is currently developing rapidly along with advances in science and technology to assist medical rehabilitation, one of which is a post-stroke rehabilitation, especially the rehabilitation of finger movement. This is also due to the human desire to help each other in accelerating the recovery of post-stroke patients. For example, the way humans walk, hold objects and others. The goal of medical rehabilitation is to maximize the functional independence and ability of patients to resume their way of life or role as before the illness and to improve the quality of life [3].

Fingers are one part of the human body playing an important role in human movement to perform various activities [4]. Humans have a total of ten fingers that function to hold objects. From the working principle of human fingers, it is then used as the basis for the development of finger robots designed to hold objects. Finger robots are one solution to help accelerate the rehabilitation process, specifically for finger movements. One of the efforts for the development of finger robots is finger motion estimation.

One of the main challenges in the development of a Finger Prosthetic Robotics Arm is how to estimate finger motion accurately. One of the estimation methods having a small error is the Ensemble Kalman Filter Square Root method, which is very reliable for both linear and nonlinear models with the addition of square root in the correction stage. The EnKF-SR method is frequently used for motion and position estimation of AUVs [5], [6], [7], ASVs [8], missiles [9] and mobile robots [10]. And for this paper, the finger motion estimation was carried out, especially for the index finger on the left hand, by using the Square Root EnKF (SR-EnKF) method, and the accuracy of the simulation results was compared when generating 250 ensembles, 500 ensembles and 750 ensembles.

2 Finger Arm Robot Model

Here is the analysis of the 3-joint finger arm robot. Figure 1 shows a 3-joint finger arm robot using forward kinematics in x and y coordinates as its equation analysis [5].

The angle Ψ is the angle of the facing direction of the third arm with respect to the X-axis, as in equation (1).

$$\Psi = (\theta_1 + \theta_2 + \theta_3). \tag{1}$$

And for the angle equation, θ_1 and θ_2 as well as Ψ are as follows:

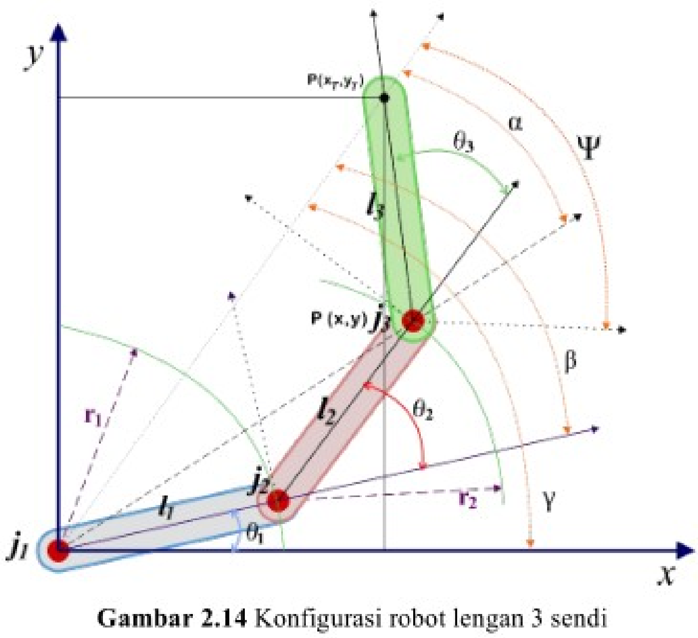

Figure 1: Configuration of the 3-joint finger arm robot [4].

$$\begin{aligned}
\theta_2 &= \cos^{-1}\left(\frac{x^2+y^2-l_1^2-l_2^2}{2l_1l_2}\right)\\
\theta_1 &= \tan^{-1}\left(\frac{y(l_1+l_2\cos\theta_2)-xl_2\sin\theta_2}{x(l_1+l_2\cos\theta_2)+yl_2\sin\theta_2}\right)\\
\Psi &= \theta_1+\theta_2+\theta_3\\
&= \sin^{-1}\left(\frac{l_1(\cos\theta_1-\sin\theta_1)+l_2(\cos(\theta_1+\theta_2)-\sin(\theta_1+\theta_2))}{2l_3}\right). \qquad (2)
\end{aligned}$$

The image of the finger arm robot is shown in Figure 2.

3 Square Root Ensemble Kalman Filter

The following is the flow of applying the mathematical model of the forefinger arm robot to the ENKF-SR algorithm, see Figure 3.

4 Simulation Results

This study was started with the aim of helping the recovery process of post-stroke patients, especially for the fingers, and more specifically, the index finger. To help improve the quality of life of patients with upper extremity paresis, this paper tries to initiate developing finger technology using a mathematical model of a finger prosthetic arm robot that has 3 joints as a motion system platform adapted to the structure of human fingers,

Figure 2: Image of a finger arm robot.

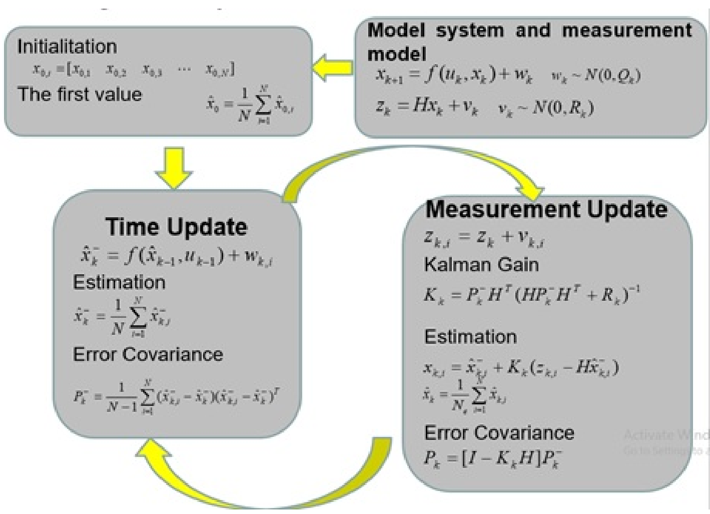

Figure 3: Ensemble Kalman Filter Square Root Algorithm [11,12,13].

especially Surabaya residents in the Republic of Indonesia, who have a ring finger length of about 7.9 - 8.2 cm. In this paper, the trajectory of the index finger movement is determined in the form of a semicircular motion, which with a movement of about 180 degrees can train the finger to improve its function and recover as before. The study in this paper implemented the Kalman Filter Square Root Ensemble method for index finger motion estimation, and for the simulation results, the accuracy comparison was made when generating 250 ensembles, 500 ensembles and 750 ensembles as shown in

Figures 4-7.

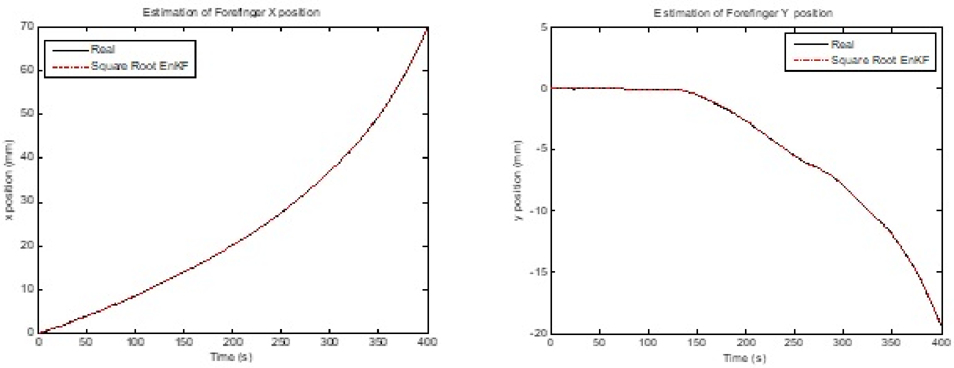

Figure 4: Motion estimation of a finger arm robot, especially the index finger, using 250 ensembles on the X-plane and Y-plane.

In Figure 4, it can be seen that the motion of the index finger in the 2-dimensional movement in the X and Y planes takes 400 seconds. From Figure 4, it can be seen that the EnKF-SR method has high accuracy with an error of about 1-2%.

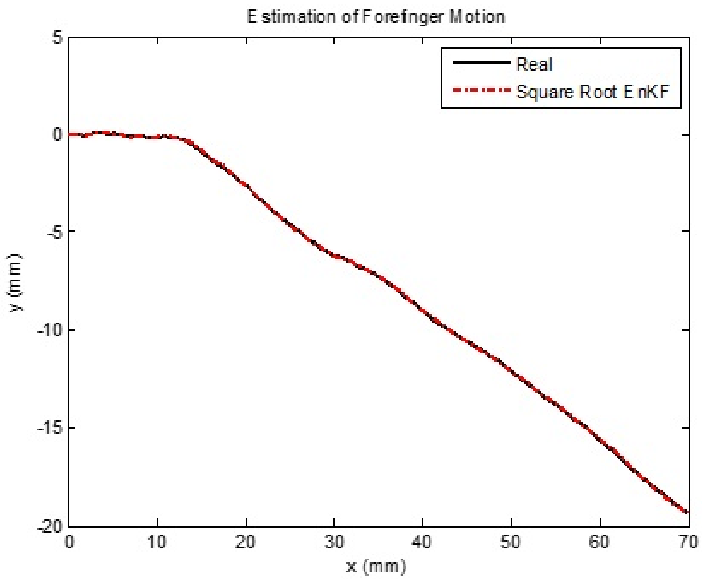

Figure 5: Motion estimation of a finger arm robot, especially the index finger, using 250 ensembles.

Figure 5 shows a semicircular motion in the XY plane, and it can be seen that the EnKF-SR method has a fairly small error. Figure 5 is the simulation result by generating 250 ensembles. The movement of the index finger that resembles a semicircle as in Figure 5 is compared to the motion of a semicircle with a diameter of about 7.9 cm, whereas in

Figure 4, it is obtained that its diameter is

$$\sqrt{7^2 + 2^2} = \sqrt{49 + 4} = \sqrt{53} = 7.3\,cm$$

so that overall, when viewed from the diameter of about 7.9 - 8.2 cm, it has an error of about 7.5%. The second and third simulations are shown in Figures 6 and 7. In the second

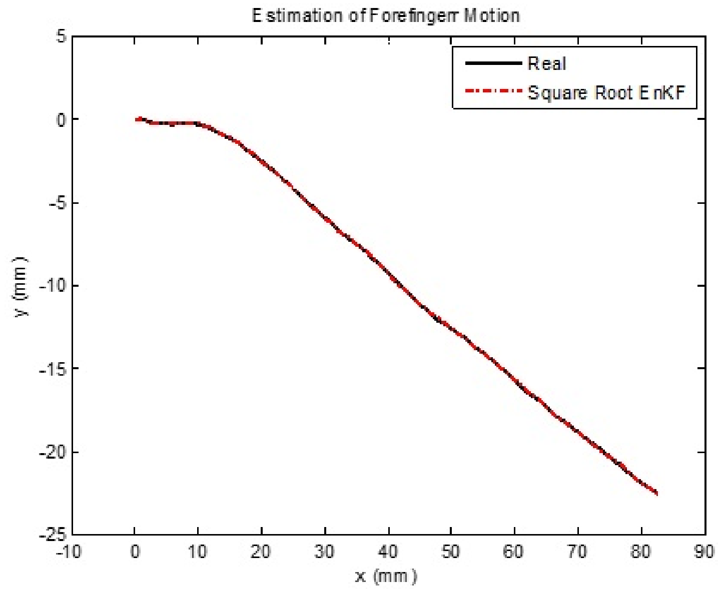

Figure 6: Motion estimation of a finger arm robot, especially the index finger, using 500 ensembles.

simulation by generating 500 ensembles, this paper displays the results of the simulations in the XY plane only as shown in Figure 6, which gives the results of simulations using the Square Root EnKF method by generating 500 ensembles resulting in movements that resemble a semicircle with a diameter of $\sqrt{8.1^2 + 2.3^2} = \sqrt{65.61 + 5.29} = \sqrt{70.9} = 8.42$ cm, so that overall, if viewed from a diameter of about 7.8 cm - 8.3 cm, then using 500 ensembles has an error of about 2.68%, in other words, it has an accuracy of about 97.32%. So, the EnKF-SR method can be effectively used to estimate the motion of the finger arm robot, especially the index finger.

Figure 7 shows a semicircular motion in the XY plane, where it can be seen that the Square Root EnKF method has a fairly small error. Figure 7 is the simulation result by generating 750 ensembles. The movement of the index finger that resembles a semicircle as in Figure 7 is compared with the motion in a semicircle with a diameter of 7.9 - 8.2 cm, where in Figure 7 the obtained diameter is $\sqrt{8.05^2 + 2.3^2} = \sqrt{64.8025 + 5.29} = \sqrt{70.0925} = 8.37$, so that overall, when viewed from a diameter of about 7.9 - 8.2 cm, it has an error of about 2.07%.

Table 1 shows that the simulation with 750 ensembles has a smaller error than those using 250 and 500 ensembles. The three simulation results are compared for the size of the index finger of the Surabaya community in Indonesia with an average length of about 7.9 - 8.2 cm, which performes a semicircular motion. So, in view of the three simulations

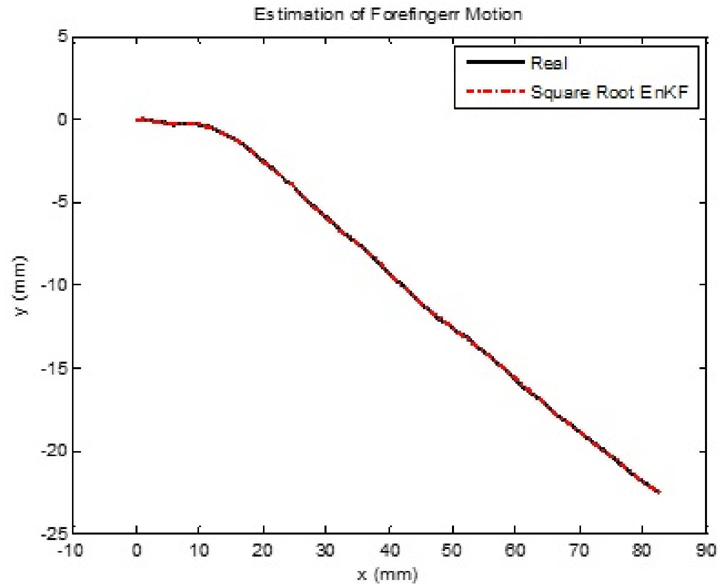

Figure 7: Motion estimation of a finger arm robot, especially the index finger, using 750 ensembles.

	250 ensembles	500 ensembles	750 ensembles
XY Motion	7.5%	2.8%	2.07%
Simulation Time	5.9 s	9.85 s	12.9 s

Table 1: Comparison of error values based on the generation of different number of ensembles by the Square Root EnKF method

above, the Square Root EnKF method can be used as a reliable estimation method in estimating the finger arm robot, having an error of not more than 8%.

5 Conclusion

Based on the analysis of the results of three simulations, comparing the simulations based on the generation of different number of ensembles, it can be concluded that the Square Root EnKF method can be used as a reliable estimation method to estimate the motion of the finger arm robot showing an error of not more than 2-3% range for the simulations generating 500 and 750 ensembles, while the simulation with 250 ensembles produces an error of 7.5% or, in other words, it has an accuracy of 92.5% . Overall, the 750 ensemble simulation has the highest accuracy as compared to those using 250 and 500 ensembles.

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References

[1] T. Herlambang, H. Nurhadi, A. Muhith, D. Rahmalia and P. B. Tomosouw. Estimation of Third Finger Motion Using Ensemble Kalman Filter. *BAREKENG: Journal of Mathematics and Its Application* **16** (3) (2022) 1079–1086.

[2] T. Herlambang, H. Nurhadi, A. Muhith, A. Suryowinoto and K. Oktafianto. Estimation of Forefinger Motion with Multi-DOF Using Advanced Kalman Filter. *Nonlinear Dynamics and Systems Theory* **23** (1) (2023) 24–33.

[3] O. S. Purwanti and A. Maliya. Rehabilitasi Klien Pasca Stroke. *Berita Ilmu Keperawatan* **1** (1) (2008) 43–46.

[4] E. S. Ningrun, B. Sumantri, B. Wijayanto, C. Yanuar and M. I. Riansyath. Optimasi Pergerakan Robot Planar 3 Sendi Pada Robot Penggenggam Menggunakan Metode Pemrograman Genetika. *Jurnal Inovtek* **3** (1) (2013) 20–25.

[5] T. Herlambang, E. B. Djatmiko, H. Nurhadi. Ensemble Kalman Filter with a Square Root Scheme (EnKF-SR) for Trajectory Estimation of AUV SEGOROGENI ITS. *International Review of Mechanical Engineering IREME Journal* **9** (6) (2015) 553–560.

[6] S. Subchan, T. Herlambang and H. Nurhadi. UNUSAITS AUV Navigation and Guidance System with Nonlinear Modeling Motion Using Ensemble Kalman Filter. In: *Proc. International Conference on Advanced Mechatronics, Intelligent Manufacture, and Industrial Automation (ICAMIMIA)* Malang, Indonesia, 2019.

[7] T. Herlambang, S. Subchan and H. Nurhadi. Navigation and Guidance Control System of UNUSAITS AUV Based on Dynamical System Using Ensemble Kalman Filter Square Root. In: *Proc. the Third Internatonal Conference on Combinatorics, Graph Teory and Network Topology* Jember, Indonesia, 2019.

[8] H. Nurhadi, T. Herlambang and D. Adzkiya. Trajectory Estimation of Autonomous Surface Vehicle Using Square Root Ensemble Kalman Filter. In: *Proc. International Conference on Advanced Mechatronics, Intelligent Manufacture, and Industrial Automation (ICAMIMIA)* Malang, Indonesia, 2019.

[9] T. Herlambang. Design of a Navigation and Guidance System of Missile with Trajectory Estimation Using Ensemble Kalman Filter Square Root (EnKF-SR). In: *Proc. International Conference on Computer Applications and Information Processing Technology (CAIPT)* Bali, Indonesia, 2019. 8–10.

[10] T. Herlambang, F. A. Susanto, D. Adzkiya, A. Suryowinoto, and K. Oktafianto. Design of Navigation and Guidance Control System of Mobile Robot with Position Estimation Using Ensemble Kalman Filter (EnKF) and Square Root Ensemble Kalman Filter (SR-EnKF). *Nonlinear Dynamics and Systems Theory.* **22** (4) (2022) 390–399.

[11] T. Herlambang, A. Muhith, D. Rahmalia, H. Nurhadi. Motion Optimization using Modified Kalman Filter for Invers-Kinematics based Multi DOF Arm Robot. *International Journal of Control and Automation.* **13** (2) (2020) 66–71.

[12] D. F. Karya, K. Puspandam and T. Herlambang. Stock Price Estimation Using Ensemble Kalman Filter Square Root Methods. *The First Internatonal Conference on Combinatorics, Graph Teory and Network Topology, University of Jember-Indonesia.* (2017) 25–26.

[13] A. Muhith, T. Herlambang, D. Rahmalia, I. Irhamah and D. F. Karya. Estimation of Thrombocyte Concentrate (TC) in PMI Gresik using unscented and square root Ensemble Kalman Filter. *The 5th International Conference of Combinatorics, Graph Theory, and Network Topology (ICCGANT)*, 2021.