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Research article

Fast calibration for parameters of an inertial measurement unit fixed to a standard walker

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A R T I C L E I N F O

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A B S T R A C T

A system consisting of an inertial measurement unit (IMU) mounted on a walker is proposed. The objective of this system is to monitor a user's walking. The relationship between the walker and the IMU, which cannot be easily measured manually, plays an important role in the system. There are various relationships because of the different types of walkers, as well as adjustments made to the height of the walker legs for comfortable usage. In this study, we propose a simple procedure for fast calibration, which consists of the attitude and the position of the IMU with respect to the walker coordinate system. The procedure includes slightly tilting the walker to the front, back, right, and left. A Kalman filter based on the inertial navigation system is used to estimate the trajectory of the IMU during tilting movements. The relationship can be calibrated using the estimated trajectory and geometric characteristics of walkers. The results of the experiments show that the proposed method achieves acceptable accuracy (97% of distance and position) and convenience.

1. Introduction

A walker, also known as a walking frame, is utilized by people requiring stability due to age-related conditions, disabilities, or for physical rehabilitation [1, 2, 3]. Additionally, the study in [4] shows that the use of walkers affects the rehabilitation outcome, and can also accelerate the recovery period.

To speed up the rehabilitation of a person aided by a walker, an assessment can be made based on the results of several experiments [5, 6]. One of the tests involves walking speed, which has been proven to be associated with survival rates of adults. A measure based on a comprehensive geriatric assessment and a responsive measure for patients experiencing short-term rehabilitation are taken into account.

Normally, several standard tests can be taken with and without walking aids, such as the 6-Minute Walk Test [7], the 50-Feet Walk Test, the 30-Second Chair Stand Test [8], and the Timed-Up and Go Test [9], to evaluate walking parameters. However, these tests pose a disadvantage when they compute average walking speed only, rather than frequently reevaluate these data, mostly because the tests are conducted in hospitals [8].

Recently, low-cost inertial measurement units (IMUs) consisting of accelerometers and gyroscopes have been successfully utilized for motion tracking. Due to their acceptable accuracy, low cost, light weight, compact size, and user-friendliness, these wearable IMUs have become one of the most preferred solutions for motion tracking. Motion tracking can be used for gait analyses [10, 11, 12], pedestrian navigation [13], the control system of an industrial robot trajectory [14, 15, 16], and sports-related applications [17, 18].

We advanced a complete and portable measurement system, consisting of an IMU and two encoders fixed to a front-wheel walker [10, 19]. The walking parameters were extracted from the walker's trajectory, estimated using a Kalman filter (KF), based on an inertial navigation system (INS) and encoders [10]. In [19], we improved the system with proposed measurement equations employing a KF. The relationship between the IMU and the walker, consisting of the attitude (represented by a rotation matrix) and position (represented by a translation vector) of the IMU in the walker coordinate system, is used to compute the position of the walker using the position of the IMU, which is manually measured. The measurement results are obtained by the experiments conducted by researchers. Therefore, when the system is available to general users, the outcomes may vary due to the different types of walkers and adjustments in the height of the walker's legs.

In this paper, we propose a method for fast calibration of the relationship using a simple procedure to extract the position and attitude of an IMU that is freely fixed to the frame of a standard walker. The procedure includes slightly tilting the walker to the front, back, right, and

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left by approximately 20°–45°. A KF based on an INS is used to estimate the movement trajectory of the IMU. We can compute the relationship based on the estimated trajectory and the geometric characteristics of walkers.

2. Methods

2.1. System overview

Our proposed system of a standard walker is shown in Figure 1, in which an IMU module consisting of an IMU and a micro SD card is freely mounted to the frame of the walker. The IMU contains a three-axis accelerometer and a three-axis gyroscope, with a sampling frequency of 100 *Hz*. The rectangle *ABCD* creates the border, as illustrated in Figure 1.

There are three coordinate systems used in this study: a world coordinate system (WCS), a body coordinate system (BCS), and an IMU coordinate system (ICS). The WCS is fixed, while the ICS and BCS are changed together during moving of the walker. The ICS coincides with the physical coordinate system of the IMU. At the beginning of the period, the x_b-axis and y_b-axis of the BCS are on the horizontal floor, while the z_b-axis points upward, as shown in Figure 2. Unlike the

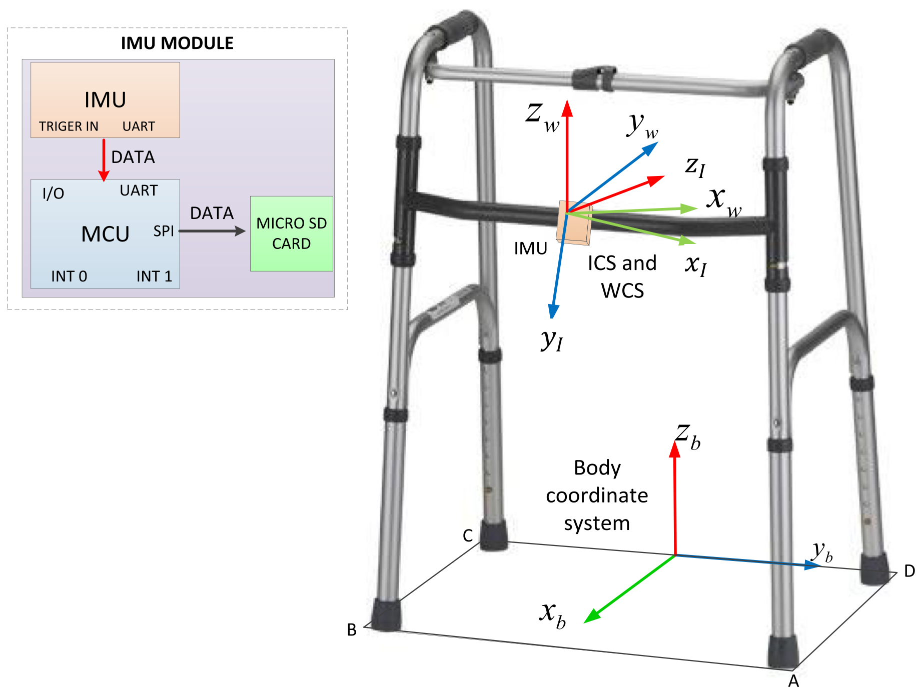

Figure 1. World coordinate system, IMU coordinate system, and body coordinate system in the proposed system.

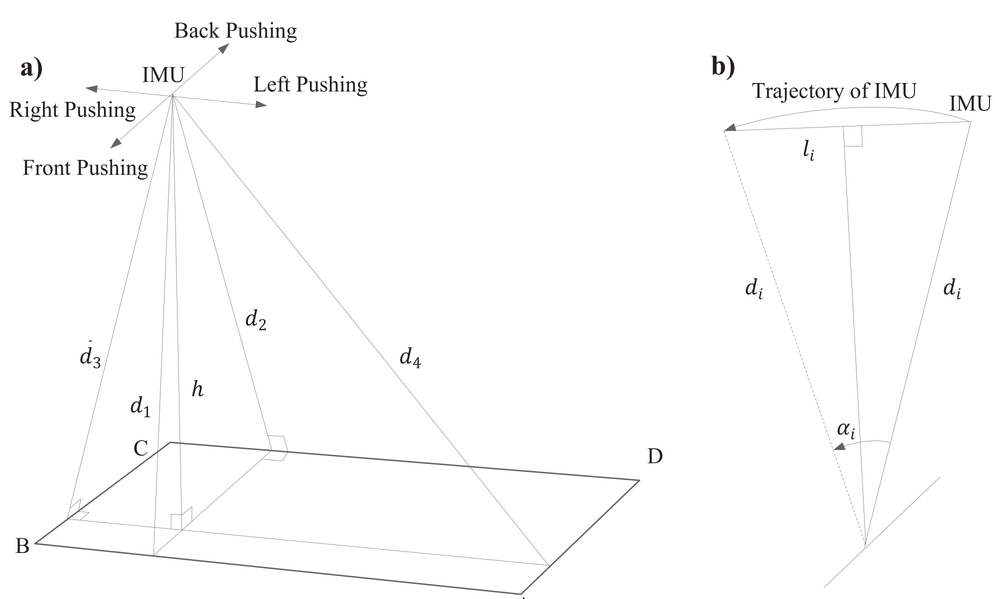

Figure 2. Fast procedure for relationship calibration: a) tilting movements, b) distance computation.

procedures followed in [10] and [19], the origin is set at the midpoint of segment CD, as illustrated in Figure 1, because the distance from the origin to the heels of a user is nearest after a moving step. The z_w-axis of the WCS points upward, while the x_w-axis is in the vertical plane with the x_I-axis. The origin of the WCS is chosen to coincide with the origin of the ICS at the beginning of the period. The notation $[a]_w$ ($[a]_b$ or $[a]_I$) refers to vector a in the WCS, BCS, or ICS, respectively.

The relationship between ICS and WCS, represented by position r and quaternion q, is estimated by the KF based on the INS (see Subsection 2.3). The relationship between ICS and BCS, consisting of the translation vector T_I^b and the rotation matrix C_I^b, is calibrated by a fast procedure in Subsection 2.2. The terms T_I^b and C_I^b are necessary for computing the walker's position using the IMU's position.

2.2. Relationship of calibration between ICS and BCS

The fast procedure for relationship calibration includes pushing the walker slightly and tilting to the front, back, right, and left by approximately 20°–45° (see Figure 2a). During the tilting period, the IMU is rotated around segment AB (CD or BC or AD) in an arc with a radius of d_1 (d_2 or d_3 or d_4), respectively, as shown in Figure 2b.

The movement of the IMU in each tilting movement is estimated by using a KF based on the INS in Subsection 2.3. From the movement trajectory, we can compute the distance of movement l_i, the rotation angle α_i, and the distance d_i from the IMU to the border segments.

2.2.1. Rotation matrix estimation

Let $r \in R^3$ and $q \in R^4$ be the trajectory and quaternion (representing the attitude of IMU in WCS), respectively, during the tilting movement. Then $C(q)$ is the rotation matrix from WCS to ICS with respect to quaternion q [20], and can be computed as

$$C(q) = \begin{bmatrix} q(4)^2 + q(1)^2 - q(2)^2 - q(3)^2 & 2(q(1)q(2) + q(4)q(3)) & 2(q(1)q(3) - q(4)q(2)) \\ 2(q(1)q(2) - q(4)q(3)) & q(4)^2 - q(1)^2 + q(2)^2 - q(3)^2 & 2(q(1)q(2) + q(4)q(1)) \\ 2(q(1)q(3) + q(4)q(2)) & 2(q(1)q(3) - q(4)q(1)) & q(4)^2 - q(1)^2 - q(2)^2 + q(3)^2 \end{bmatrix}, \quad (1)$$

where $q = [\, q(1) \quad q(2) \quad q(3) \quad q(4)\,]$.

Following the definition of the rotation matrix, the rotation matrix from BCS to WCS at the beginning of the period is defined as

$$C_{b1}^{w} = [\, x_{b1} \quad y_{b1} \quad z_{b1}\,], \quad (2)$$

where x_{b1}, y_{b1}, and z_{b1} are the axes of the BCS at the beginning of period. At that time, the walker is standing on the floor. Therefore, x_{b1} is pointing toward and in a horizontal plane, and z_{b1} is pointing upward.

The x_{b1}-axis can be estimated by the backward tilting movement. The moving direction vector of the IMU in this movement is in the vertical plane with the x_{b1}-axis. The direction vector can be computed as

$$dv_i = r_1 - r_N, \quad (3)$$

where r_i is the position of the IMU in the WCS at a discrete-time index i, and is estimated using a KF based on the INS; $i = 1$ and $i = N$ are the initial and final discrete-time index of the tilting movement, respectively.

The x_{b1}-axis in WCS can be computed by

$$x_{b1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} dv_i. \quad (4)$$

Since the x_{b1}-axis is a unit vector, x_{b1} should be normalized by

$$x_{b1} = \frac{x_{b1}}{\|x_{b1}\|}. \quad (5)$$

Since the z_{b1}-axis is pointing upward while the walker is standing on the horizontal floor, $z_{b1} = [\,0 \quad 0 \quad 1\,]'$. The rotation matrix from BCS to WCS at the beginning of the tilting movement can be computed as

$$C_{b1}^{w} = [\, x_{b1} \quad z_{b1} \times x_{b1} \quad z_{b1}\,]. \quad (6)$$

The rotation matrix from ICS to BCS can be computed as

$$C_I^b = C_{b1}^{w} C'(q_1), \quad (7)$$

where q_1 is quaternion q at the beginning of the tilting movement and is estimated using a KF based on the INS.

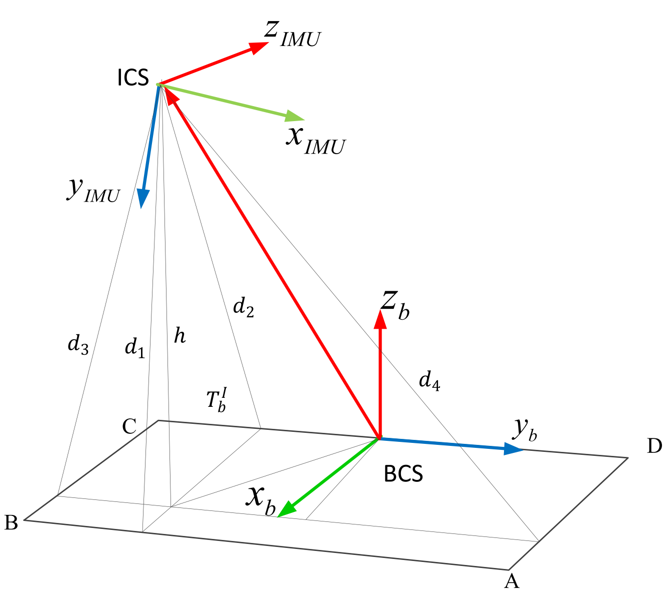

Figure 3. Translation vector from BCS to ICS.

2.2.2. Translation vector estimation

The fast procedure for calibrating the translation vector is shown in Figure 2a, in which the length of d_i ($i = 1:4$) can be computed as illustrated in Figure 2b. As can be seen, d_i can be computed by using the movement distance l_i and the rotation angle α_i in each tilting movement. Since l_i is equal to the length of dv_i computed in (3), $l_i = \|dv_i\|$.

Next, we compute the rotation angle α_i around a rotation axis. The rotation matrix from ICS at the end to BCS at the beginning can be computed as

$$C_{IN}^{b1} = C_{b1}^{\prime w} C'(q_N). \quad (8)$$

The rotation matrix from BCS at the end to BCS at the beginning can be computed as

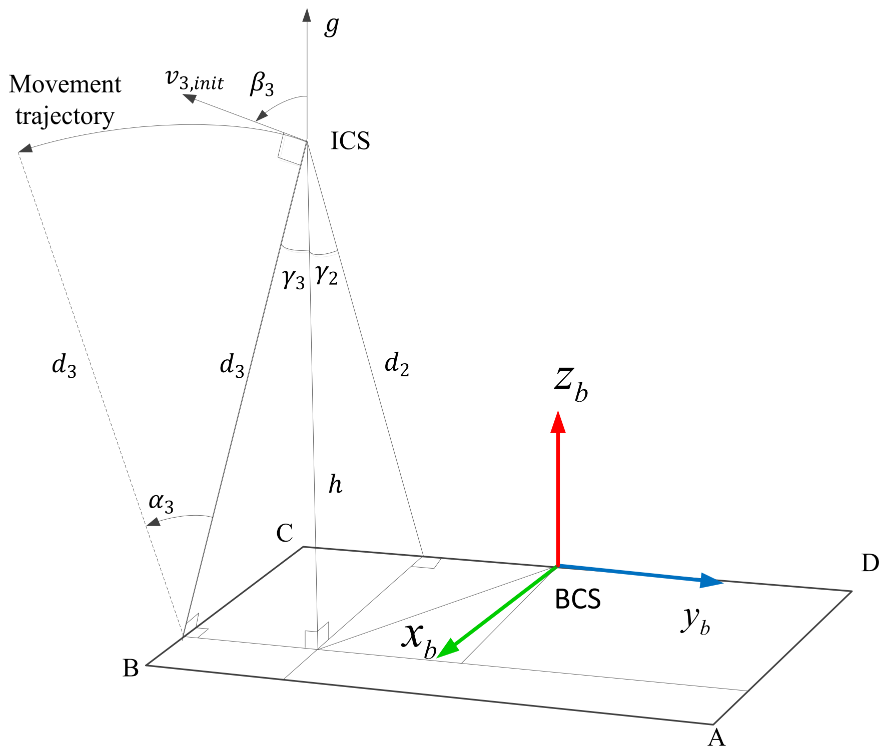

Figure 4. Translation vector from BCS to the ICS using directional vector.

$$C_{bN}^{b1} = C_{b1}^{'w} C^{'}(q_N) C_I^{'b}. \tag{9}$$

Let q_{ff} be the quaternion with respect to rotation matrix C_{bN}^{b1}, where q_{ff} represents the rotation of the walker around segment CD (y_b-axis) during the backward tilting movement. Therefore, the quaternion $q_{ff} = \begin{bmatrix} q_{ff}(1) & q_{ff}(2) & q_{ff}(3) & q_{ff}(4) \end{bmatrix}$ can be computed from the rotation matrix C_{bN}^{b1} as follows:

$$\begin{aligned} q_{ff}(1) &= \frac{1}{2}\sqrt{C_{11} + C_{22} + C_{33} + 1} \\ q_{ff}(2) &= \frac{C_{23} - C_{32}}{4q_{ff}(1)} \\ q_{ff}(3) &= \frac{C_{31} - C_{13}}{4q_{ff}(1)} \\ q_{ff}(4) &= \frac{C_{12} - C_{21}}{4q_{ff}(1)} \end{aligned}, \tag{10}$$

where C_{ij} is an element in row i and column j of rotation matrix C_{bN}^{b1}.

In addition, quaternion q_{ff} is defined as follows:

$$q_{ff} = \left[\cos\frac{\alpha_i}{2} \quad \sin\frac{\alpha_i}{2} u_i \right] \in R^4, \tag{11}$$

where $u_i \in R^3$ and α_i are the rotation axis and rotation angle of the tilting movement i, respectively; $u_i \equiv y_b$ during the front/back, and $u_i \equiv x_b$ during the left/right tilting movement.

The term α_i is computed as follows:

$$\alpha_i = 2\cos^{-1}(q_{ff}(1)) \tag{12}$$

The value of d_i is computed by using l_i and α_i as follows:

$$d_i = \frac{l_i}{2\sin\frac{\alpha_i}{2}} \tag{13}$$

From Figure 2a, the height of the IMU can be computed using d_1, d_2 or d_3, d_4. In this paper, we use all the terms d_1, d_2, d_3, d_4 to improve the precision of estimation:

$$h = \frac{\sqrt{p_1(p_1 - AB)(p_1 - d_3)(p_1 - d_4)}}{AB} + \frac{\sqrt{p_2(p_2 - AD)(p_2 - d_1)(p_2 - d_2)}}{AD}, \tag{14}$$

where $p_1 = \frac{AB + d_3 + d_4}{2}$ and $p_2 = \frac{AD + d_1 + d_2}{2}$.

As demonstrated in Figure 3, the translation vector T_b^I is computed by

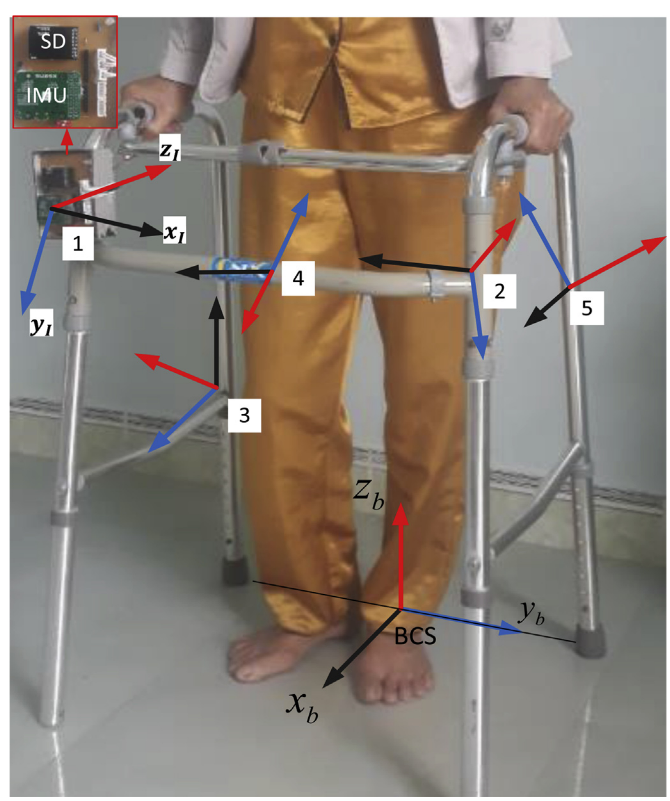

Figure 5. Walker system for experiment with five poses of IMU module.

Table 1. Relationship between ICS and BCS for five different poses of the IMU.

Pose	C_I^b	T_b^I
1	$\begin{bmatrix} 0.1563 & 0.0119 & -0.9876 \\ 0.9873 & 0.0250 & 0.1565 \\ 0.0266 & -1.0017 & -0.0079 \end{bmatrix}$	$T_{b1}^I = [0.4589 \quad -0.2120 \quad 0.6268]'$ $T_{b2}^I = [0.4039 \quad -0.3259 \quad 0.6390]'$
2	$\begin{bmatrix} 0.1563 & -0.6062 & -0.7229 \\ -0.9318 & -0.0898 & -0.3507 \\ 0.1478 & 0.7900 & -0.5950 \end{bmatrix}$	$T_{b1}^I = [0.4996 \quad 0.0159 \quad 0.6570]'$ $T_{b2}^I = [0.4713 \quad 0.1857 \quad 0.6563]'$
3	$\begin{bmatrix} 0.0426 & -0.8700 & -0.4902 \\ 0.0618 & 0.4920 & -0.8678 \\ 0.9972 & 0.0066 & 0.0749 \end{bmatrix}$	$T_{b1}^I = [0.1944 \quad -0.2489 \quad 0.3580]'$ $T_{b2}^I = [0.1990 \quad -0.1098 \quad 0.3262]'$
4	$\begin{bmatrix} -0.1929 & -0.5562 & 0.8080 \\ -0.9442 & 0.3286 & 0.0008 \\ -0.2660 & -0.7632 & -0.5888 \end{bmatrix}$	$T_{b1}^I = [0.4554 \quad -0.1453 \quad 0.5755]'$ $T_{b2}^I = [0.3201 \quad -0.1009 \quad 0.6159]'$
5	$\begin{bmatrix} -0.6299 & -0.4139 & -0.6566 \\ -0.4547 & -0.4886 & 0.7442 \\ -0.6293 & 0.7679 & 0.1196 \end{bmatrix}$	$T_{b1}^I = [0.0917 \quad 0.0264 \quad 0.5654]'$ $T_{b2}^I = [0.0051 \quad 0.0821 \quad 0.5870]'$

$$T_b^I = \begin{bmatrix} \sqrt{d_2^2 - h^2} \\ \frac{1}{2}\left(\sqrt{d_3^2 - h^2} - \sqrt{d_4^2 - h^2}\right) \\ h \end{bmatrix}. \tag{15}$$

From (7) and (15) we can see that the relationship between ICS and BCS is immediately calibrated with the aid of a fast and simple procedure, including tilting the walker to the front, back, right, and left.

In order to simplify the procedure, the initial velocity of the IMU is used. In this case, the procedure just includes tilting movements to the back and the right. The translation vector T_b^I is computed using the initial velocity $v_{i,init}$ and the upward vertical vector g, as shown in Figure 4. The term $v_{i,init}$ in WCS is estimated in the KF based on the INS, and $g = [0 \quad 0 \quad 1]'$ coincides with z_b in WCS. The angle between the two vectors $(g, v_{i,init})$ is computed by

$$\beta_3 = \cos^{-1}\left(\frac{g v_{i,init}}{\|g\| \|v_{i,init}\|}\right) \tag{16}$$

From Figure 4, γ_3 can be computed as

$$\gamma_3 = \frac{\pi}{2} - \beta_3 \tag{17}$$

The angle γ_2 is similarly computed. The height of the IMU in BCS can be computed by

$$h = \frac{d_2 \cos(\gamma_2) + d_3 \cos(\gamma_3)}{2} \tag{18}$$

From Figure 4, the translation vector T_b^I can be computed as follows:

$$T_b^I = \begin{bmatrix} d_2 \sin(\gamma_2) \\ d_3 \sin(\gamma_3) - \frac{CD}{2} \\ h \end{bmatrix} \tag{19}$$

Thus, the procedure for calibrating the translation vector just uses two tilting movements and only involves manually measuring the distance between the two back legs.

The procedure for the rotation matrix and translation vector estimation can be summarized as follows.

Parameter estimation procedure	
1. Estimate the rotation matrix C_I^b (Subsection 2.2.1)	
• Compute x_{b1} according to (5), using:	r from the KF
• Compute $z_{b1} = [0 \quad 0 \quad 1]'$	
• Compute C_{b1}^w according to (6), using:	x_{b1}, z_{b1}
• Compute C_I^b according to (7), using:	C_{b1}^w
2. Compute d_i for eachtilting movement (Subsection 2.2.2)	
• Compute $l_i = \|dv_i\|$, using:	r from the KF
• Compute α_i according to (12), using:	q from the KF
• Compute d_i according to (13), using:	l_i, α_i
3. Estimate translation vector T_I^b (Subsection 2.2.2)	
a. First method:	
• Compute h according to (14), using:	AB, AD, d_1, d_2, d_3, d_4
• Compute T_I^b according to (15), using:	h, d_2, d_3, d_4
b. Second method:	
• Compute angle γ_2, γ_3 according to (17), using:	v from the KF
• Compute h according to (18), using:	γ_2, γ_3, d_2, d_3
• Compute T_I^b according to (19), using:	h, d_2, d_3, CD

2.3. The kalman filter based on the INS

The trajectory of the IMU is estimated using the basic KF based on the INS, which is not a new result, and can be found in [19, 21, 22]. The trajectory consists of position r, quaternion q, and velocity v of the IMU in the WCS.

The terms r, q, and v, used in Subsection 2.2, are related as follows:

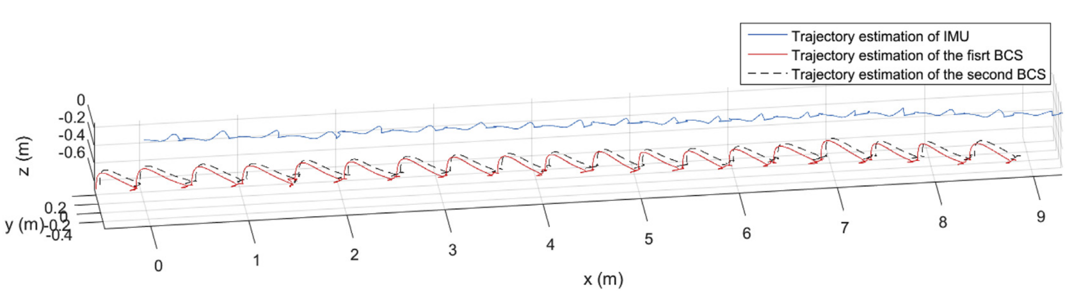

Figure 6. Movement trajectory estimation of the walker along a corridor.

Table 2. Distance estimation for walking 10 m along a corridor.

Pose	Time	Distance Estimation (m)	Distance Error (m)
1	1	9.6759	0.3241
	2	9.8406	0.1594
	3	9.824	0.176
	4	9.7334	0.2666
	5	9.7721	0.2279
	6	10.0122	0.0122
	Average	*9.8097*	*0.1944*
2	1	9.6565	0.3435
	2	9.8341	0.1659
	3	9.7267	0.2733
	4	9.7761	0.2239
	5	9.6848	0.3152
	6	9.706	0.294
	Average	*9.7307*	*0.2693*
3	1	10.3207	0.3207
	2	10.3282	0.3282
	3	10.3025	0.3025
	4	10.2189	0.2189
	5	10.4172	0.4172
	6	10.1009	0.1009
	Average	*10.2814*	*0.2814*
4	1	9.516	0.484
	2	9.6238	0.3762
	3	9.5649	0.4351
	4	9.5649	0.4351
	5	9.5932	0.4068
	6	9.5092	0.4908
	Average	*9.562*	*0.438*
5	1	9.6525	0.3475
	2	9.534	0.466
	3	9.7387	0.2613
	4	9.6749	0.3251
	5	9.6464	0.3536
	6	9.4828	0.5172
	Average	9.6525	*0.3785*
Average		**9.8011**	***0.3123***

$$\dot{q} = \frac{1}{2}\begin{bmatrix} 0 & -\omega(1) & -\omega(2) & -\omega(3) \\ \omega(1) & 0 & \omega(3) & -\omega(2) \\ \omega(2) & -\omega(3) & 0 & \omega(1) \\ \omega(3) & \omega(2) & -\omega(1) & 0 \end{bmatrix} q, \quad \dot{v} = C'(q)[a]_I, \quad \dot{r} = v \tag{20}$$

where $\omega = [\omega(1) \quad \omega(2) \quad \omega(3)]$ is the angular velocity of the ICS with respect to the WCS; and $a \in R^3$ is the acceleration of the IMU.

The outputs of the IMU, consisting of the output of accelerometers ($o_a \in R^3$)and gyroscope ($o_g \in R^3$), are given by

$$o_a = [a]_I + C(q)g + n_a, \quad o_g = \omega + n_g \tag{21}$$

where $n_a = b_a + v_a \in R^3$ and $n_g = b_g + v_g \in R^3$ are the noise of the accelerometer and the gyroscope, respectively, in which $v_a \in R^3$ and $v_g \in R^3$ are white noise, and $b_a \in R^3$ and $b_g \in R^3$ are biases of the noise; $g \in R^3$ is the local gravitational vector in the WCS.

Eq. (20) is integrated by replacing $[a]_I$ with $o_a - C(q)g$ and replacing ω with o_g. Let $\hat{q} \in R^3, \hat{r} \in R^3, \hat{v} \in R^3$ be the integrated values, and $\overline{q} \in R^3$, $\overline{r} \in R^3$, $\overline{v} \in R^3$ be the error due to the IMU noise. They are related as follows:

$$\overline{q} = [0_{3\times1} \& I_{3\times3}](\hat{q}^* \otimes q), \quad \overline{r} = r - \hat{r}, \quad \overline{v} = v - \hat{v} \tag{22}$$

where $\otimes$ is quaternion multiplication and a^* is the quaternion conjugate of quaternion a.

The state of the KF is as follows:

$$x(t) = \begin{bmatrix} \overline{q} \\ b_g \\ \overline{r} \\ \overline{v} \\ b_a \end{bmatrix}. \tag{23}$$

The system equation for the KF is as follows:

$$\dot{x}(t) = A(t)x(t) + w(t), \tag{24}$$

where

$$A(t) = \begin{bmatrix} [-o_g\times] & -\frac{1}{2}I_{3\times3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{3\times3} & 0 \\ & 0 & 0 & 0 & 0 \\ -2C'(\hat{q})[o_a\times]0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad w(t) = \begin{bmatrix} -\frac{1}{2}v_g \\ v_{bg} \\ 0 \\ -C'(\hat{q})v_a \\ v_{ba} \end{bmatrix},$$

and $[o_a \times] \in R^{3\times3}$ is the skew-symmetric matrix of vector $o_a \in R^3$; v_{bg} and v_{ba} are the noise, which represents the small variation of biases.

During walking, there are intervals when the walker is on the horizontal floor and not moving. Since the velocity and the height of the walker are almost zero, the error in the velocity and the third component of the walker's position can be reset. The algorithm to detect the zero velocity intervals and the updating equations for the KF at the intervals can be found in [19].

2.4. Experiments

The walker system used for the experiments to evaluate the accuracy of the proposed algorithm is shown in Figure 5. The walking data are recorded by the IMU (model MTi-1, 100 Hz, Xsens, Netherlands) and stored in a micro SD card. The purpose of this section is to verify that the proposed calibration method, which can be used to estimate the relationship between ICS and BCS when the IMU is set anywhere in the frame of the walker, and the estimated relationship can be used to estimate the movement trajectory of the walker during walking.

Two experiments are implemented in this study, in which two elderly people (a male and a female) are asked to walk 10 m along a corridor and 17.5 m along a rectangle trajectory (5 $m \times 3.75$ m) using the walker system. The participants received written informed consent and voluntarily agreed to participate in the experiments. The experimental protocol was approved by The University of Danang – University of Technology and Education, Vietnam.

The IMU module is mounted to the walker in five different poses (position and attitude), as shown in Figure 5. The ICS, numbered from 1 to 5, is set in five different positions of the walker, and the direction of the axes is changed in each position. The x-, y-, and z-axes of the coordinate systems are in black, blue, and red colors, respectively. The estimated rotation matrix C_I^b and the estimated translation vector T_b^I for five different poses are shown in Table 1. The term $T_{b,1}^I$ is the translation

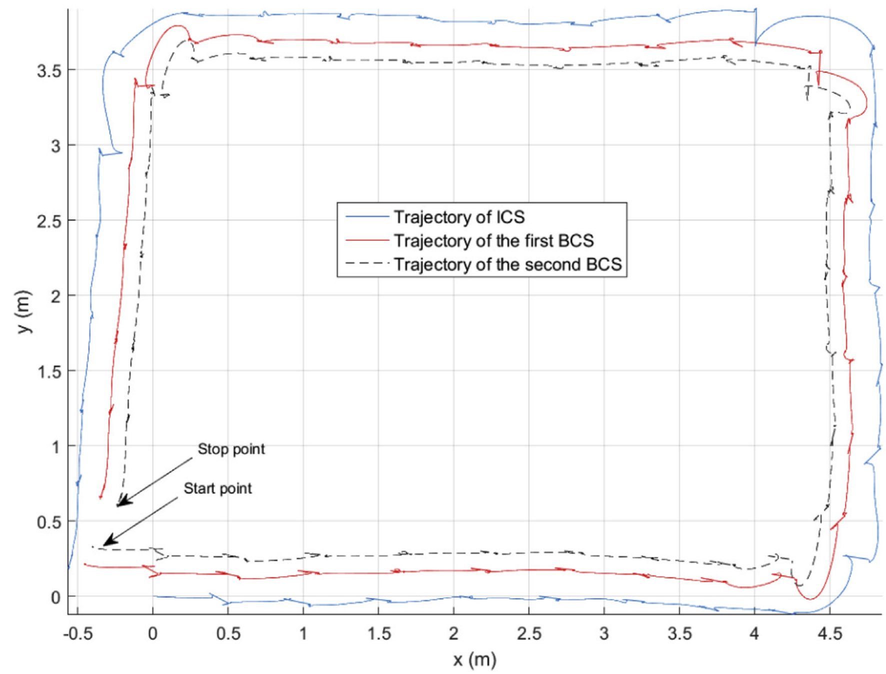

Figure 7. Movement trajectory estimation of the walker around a rectangular shape.

vector computed by (15) using the full procedure consisting of four tilting movements, while $T_{b,2}^{I}$ is computed by (19) using the fast procedure consisting of two tilting movements. Since it is difficult to evaluate the accuracy of parameters in Table 1, and the main purpose of the proposed system is to estimate the walking parameters using the trajectory of the walker, we implemented two experiments to evaluate the accuracy of the proposed system by the estimated distance and position, in which the trajectory of the walker (BCS) is computed from the trajectory of the IMU using the rotation matrix C_I^b and translation vector T_b^I [19]:

$$r_{b,i} = r_i - C_{b,i}^{w} T_b^I \tag{25}$$

where $r_{b,i}$ is the position of the BCS; and $C_{b,i}^{w} = \left(C_I^b C(q_i)\right)^T$ is the rotation matrix from the BCS to the WCS at discrete-time index i.

3. Results

In the first experiment, two elderly people were asked to walk 10 m along a corridor using the walker. Two elderly people walked six times along the corridor in each pose of the IMU with the walker. The movement trajectory of the walker during walking was estimated, and is shown in Figure 6, in which the blue line, the red line, and the black dashed line show the movement trajectory of the ICS, the first BCS (with respect to $T_{b,1}^{I}$), and the second BCS (with respect to $T_{b,2}^{I}$), respectively. The results of the experiment are shown in Table 2, consisting of the distance estimation and the distance error. In this experiment, every point in the walker travels the same distance from the starting point to the ending point. Thus, the ICS is only set at pose 1 and only $T_{b,2}^{I}$ is used to evaluate the accuracy in the proposed system. The average distance estimation is 9.8011 m and the average distance error is 0.3123 m. Thus, the accuracy of distance estimation using the walker system is approximately 97%. This is an acceptable accuracy in terms of walking parameter estimation.

In the second experiment, the same elderly participants (a man and a women) were asked to walk around a rectangular trajectory ($5\ m \times 3.75\ m$) using the walker. The participants walked six times along the rectangle in each pose of the IMU. Figure 7 shows the estimated trajectory of the IMU and the walker, in which the blue line, the red line, and the black dashed line show the movement trajectory of the ICS, the first BCS (with respect to $T_{b,1}^{I}$), and the second BCS (with respect to $T_{b,2}^{I}$), respectively. The starting point and the ending point must be in the same position. To evaluate the accuracy of the estimation, the position error between the estimated starting point and the estimated ending point is used. The results of the experiment are displayed in Table 3 for the first BCS, and in Table 4 for the second BCS, consisting of the position error and the distance error. The position error in the z-axis is equal to zero because the height of the BCS is reset when the walker is standing on the floor. By comparing the different poses in Tables 3 and 4, the conclusion in which there is a small difference of position error and distance error using the first and second estimated BCS can be reached. However, the average position errors of the x, y, z distance errors are -0.3019 m, 0.2849 m, 0.517 m using the first estimated BCS and -0.33374 m, 0.2012 m, 0.5041 m using the second estimated BCS, respectively. Thus, the first and the second methods for estimating T_b^I give the same performance with a distance error of approximately 3%, while the procedure of the second method for estimating T_b^I consists of only two tilting movements and requires manual measurement of the distance between the two legs of the walker. The distance is not altered significantly when the height of the walker legs is adjusted. Thus, the second method for estimating the translation vector is better than the first method. The average distance error is approximately 3% (0.517 m per 17.5 m walking). This is an acceptable error for walking parameter estimation.

4. Discussion and conclusions

In this paper, we proposed a fast procedure for the relationship estimation between an IMU and a walker, consisting of a rotation matrix and a translation vector from the BCS to the ICS. The purpose of this research study is to easily apply the IMU to various types of standard walkers and to calibrate the relationship when the users adjust the height of the walker legs for comfortable use.

The procedure consists of four types of tilting of the walker to the front, back, right, and left. The tilting movements rotate the walker and the IMU along an arc of approximately 20°–45° around a segment connecting two tips on one side of the walker legs. The movements of the IMU are estimated using a KF based on the INS.

The rotation matrix from the ICS to the BCS is estimated using the gravity acceleration vector measured by the IMU while the walker is standing on the floor, and backward tilting is estimated by a KF based on the INS. The translation vector from BCS to ICS is computed using the moving distance, the rotation angle, and the moving direction estimated in each tilting movement. There are two methods, having the same performance, to estimate the translation vector from BCS to ICS. The first method is more complex due to the implementation of four tilting movements. The second method is simpler owing to the implementation of only two tilting movements.

Two experiments were conducted to verify the accuracy of the proposed method. In these experiments, two participants, consisting of an elderly male and female, were asked to push the walker system along a corridor of 10 m and a rectangle with a perimeter of $17.5m$ ($5m \times 3.75m$). The results of the experiments show that the accuracy of the estimated distance and position is approximately 97%. This is an acceptable error for walking parameter estimation.

In comparison with other research studies, the results of [10] and [19] were used, in which the translation vector is manually and carefully measured. Because there is no rolling movement for the standard walker, the results of the lifting case in [10] and [19] were used in the comparison. In the lifting case, the accuracy of distance was estimated at approximately 98.3% in [10], 98.5% in [19], and 97% in this study. Thus, there is no significant reduction in the accuracy of the distance estimation using the fast procedure for relationship estimation between the IMU and the walker.

To evaluate the effect of the inaccuracy of the estimated translation vector for the walker's trajectory estimation, (25) must be analyzed, in which the position of the walker $r_{b,i}$ is computed using the position of the IMU in the WCS, r_i, and the estimated parameters. The error of component r_i depends on the KF based on the INS (see Subsection 2.3) and is independent of the estimated parameters. The error of the component $C^w_{b,i}T^I_b$ is directly dependent on the estimated parameters. Let Tt^I_b and Te^I_b be the true and error components of the estimated translation vector T^I_b. We have

$$C^w_{b,i}T^I_b = C^w_{b,i}Tt^I_b + C^w_{b,i}Te^I_b \tag{26}$$

Let N be the discrete-time index at the end of walking. The walking length is computed as

Table 3. Position error of walking around rectangular trajectory for the first estimated BCS.

Pose	Time	Position Error (m)			
		x	y	z	Distance
1	1	-0.6862	0.3594	0	0.7746
	2	-0.5807	0.4075	0	0.7094
	3	-0.8464	0.6528	0	1.0689
	4	-0.6808	0.6143	0	0.9170
	5	-0.6101	0.6441	0	0.8872
	6	-0.6458	0.5006	0	0.8171
	Average	*-0.675*	*0.5298*	*0*	*0.8624*
2	1	-0.3796	0.0109	0	0.3797
	2	-0.4917	0.1948	0	0.5289
	3	-0.5011	-0.0932	0	0.5096
	4	-0.6713	0.3480	0	0.7561
	5	-0.6504	0.1789	0	0.6745
	6	-0.5267	0.4129	0	0.6692
	Average	*-0.5368*	*0.1754*	*0*	*0.5863*
3	1	-0.0993	0.4949	0	0.5048
	2	-0.0021	0.3182	0	0.3182
	3	0.1467	0.3655	0	0.3938
	4	0.1583	0.1980	0	0.2535
	5	-0.0044	0.4447	0	0.4447
	6	0.1977	0.1506	0	0.2485
	Average	*0.0662*	*0.3286*	*0*	*0.3606*
4	1	-0.0642	0.0219	0	0.0678
	2	0.0342	-0.2935	0	0.2955
	3	0.1847	-0.3248	0	0.3736
	4	-0.1239	0.1176	0	0.1708
	5	-0.2359	0.1543	0	0.2819
	6	-0.1923	0.1258	0	0.2298
	Average	*-0.0662*	*-0.0331*	*0*	*0.2366*
5	1	-0.0905	0.3404	0	0.3523
	2	-0.4053	0.3613	0	0.5429
	3	-0.1558	-0.0203	0	0.1571
	4	-0.5073	0.7896	0	0.9385
	5	-0.3684	0.6604	0	0.7562
	6	-0.2596	0.4130	0	0.4878
	Average	*-0.2978*	*0.4241*	*0*	*0.5391*
Average		-0.3019	0.2849	0	0.5170

Table 4. Position error of walking around rectangular trajectory for the second estimated BCS.

Pose	Time	Position Error (m)			
		x	y	z	Position
1	1	-0.5790	0.2923	0	0.6486
	2	-0.4699	0.3465	0	0.5839
	3	-0.7432	0.5798	0	0.9426
	4	-0.5719	0.5500	0	0.7935
	5	-0.5088	0.5684	0	0.7628
	6	-0.5370	0.4363	0	0.6919
	Average	*-0.5683*	*0.4622*	*0*	*0.7372*
2	1	-0.5508	-0.0050	0	0.5508
	2	-0.4783	0.0234	0	0.4788
	3	-0.4820	-0.2641	0	0.5496
	4	-0.6839	0.1765	0	0.7063
	5	-0.6558	0.0070	0	0.6558
	6	-0.5519	0.2428	0	0.6029
	Average	*-0.5671*	*0.0301*	*0*	*0.5907*
3	1	-0.2389	0.4977	0	0.5520
	2	-0.1415	0.3272	0	0.3565
	3	0.0071	0.3605	0	0.3605
	4	0.0187	0.1934	0	0.1943
	5	-0.1439	0.4515	0	0.4738
	6	0.0583	0.1409	0	0.1525
	Average	*-0.0734*	*0.3285*	*0*	*0.3483*
4	1	-0.1013	-0.1157	0	0.1538
	2	0.0102	-0.4341	0	0.4342
	3	0.1650	-0.4660	0	0.4944
	4	-0.1686	-0.0176	0	0.1695
	5	-0.2937	0.0241	0	0.2947
	6	-0.2459	-0.0062	0	0.2460
	Average	*-0.1057*	*-0.1693*	*0*	*0.2988*
5	1	-0.1579	0.2633	0	0.3070
	2	-0.4755	0.2866	0	0.5552
	3	-0.2250	-0.0959	0	0.2446
	4	-0.5909	0.7303	0	0.9394
	5	-0.4507	0.5995	0	0.7500
	6	-0.3338	0.3421	0	0.4780
	Average	*-0.3723*	*0.3543*	*0*	*0.5457*
Average		-0.3374	0.2012	0	0.5041

$$\left\| r_{b,N} - r_{b,1} \right\| = \left\| r_N - r_1 + C^w_{b,1} T^I_b - C^w_{b,N} T^I_b \right\| \tag{27}$$

By using the results in (26) for (27), we have

$$\left\| r_{b,N} - r_{b,1} \right\| = \left\| r_N - r_1 + \left(C^w_{b,N} - C^w_{b,1} \right) Tt^I_b - \left(C^w_{b,N} - C^w_{b,1} \right) Te^I_b \right\| \tag{28}$$

As can be seen in (28), the component of the walking length error affected by the inaccuracy of the estimated translation vector is $(C^w_{b,N} - C^w_{b,1})Te^I_b$. In general, the error is proportional to the difference of the walker's attitude at the beginning and the end of walking. This means that the estimated parameters affect the walking length error for changing direction (see Figure 7), but they do not affect the error in walking along a straight path (see Figure 6).

Although the proposed procedure for relationship estimation is only derived for a standard walker, it can be applied to a front-wheeled walker by using the second method (two tilting movements) under the assumption that the border *ABCD* is a rectangular shape. The first method (four tilting movements) cannot be directly applied to a front-wheeled walker because the walker can be rotated during tilting to the front.

Declarations

Author contribution statement

Quang Vinh Doan: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Duy Duong Pham: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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