IMU Sensor based Human Motion Detection and Its Application to Braking Control of Electric Wheeled Walker for Fall-prevention

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With the increase in the aging population of developed countries, the demand for walking assisting devices has grown. Walkers are widely used because they provide high mobility and safety. In this paper, an electric wheeled walker (EWW) is used to prevent the user from falling down. This paper presents novel fall prevention systems that are composed of a human motion detecting algorithm and a braking system. The motion detecting algorithm focuses on the reaction torque of the EWW and the acceleration of the user. The reaction torque is estimated by the reaction torque observer (RTOB), and the acceleration is measured by using one IMU sensor. The braking system works by switching commands on the basis of human motion. Four motions are considered, and if the user motion is detected as dangerous, the command value switches, and braking is initiated in response to the user posture. Experiments are performed to verify the effectiveness of the proposed algorithm and controller.

Keywords: fall prevention, walking assistance, motion detection, reaction torque observer (RTOB), compliance control, sensor

1. Introduction

Recently, developed countries have problems with the decreasing birthrate and aging population. It is assumed that more and more elderlies need nursing. The number of welfare facilities and care workers is increasing, and the rate of people who lives alone and aged over 65 is getting higher. So, assistive device for elderlies to live themselves is demanded.

Walking is one of the important element for elderlies to live their lives independently. Activity area of elderlies changes whether they can walk by themselves or not. Maintaining the ability to walk often make their quality of life (QOL) higher. A lot of people who cannot walk by themselves use a wheelchair. However, if people only use a wheelchair and won’t try to walk, people are restricted to use their muscle. Then, the decline of muscular strength will be promoted and that will lead to be bedridden. So it is important for elderlies to prevent the decline of their walking function.

Therefore, assistive devices which promote walking randomly have been gaining attention recently. Especially, walkers are popular among handicapped people, because walkers have both high mobility and safety. Recently, collaboration between robot technology and welfare sector has also been paying attention. For instance, Murata Manufacturing Co., Ltd. developed electric walking assist device named "KeePace" in 2012. This machine uses gyro sensor, which detects the slope of the device, then control by itself not to fall down. Walkers are safe and have high mobility, however fatal accidents sometimes happen. Main reason of the accident is falling down. According to National Consumer Affairs Center of Japan (NCAC), 90 percent of the fatal accidents were derived from falling down when people use walkers. Once elderlies fall down, it will cause bedridden, then that makes them difficult to walk independently.

To solve these problems, some researches have conducted which detect human motion by using sensors. Hirata et al. stopped walkers automatically detecting pitch, roll angles of upper limb and distance between user and EWW by using stereo camera. In this research, EWW detects user’s posture then put on the brake automatically when the user is in danger. Pei Di et al. presented cane robot and Zero Moment Point (ZMP) stabilization. In this paper, on-shoe sensor was proposed and detected ZMP to stabilize human posture. EWW described Kikuchi et al. implements a Web camera in front of EWW and detects obstacles, then generates the trajectory to avoid. Cong Zong et al. installed 3D camera and infrared sensor to propose motion capturing system. The subject was detected whole body, then conversed to 3D data. A.K. Bourke et al. presented motion detecting algorithm that distinguish between Activities of Daily Living (ADL) and falling down. Human motion was detected by using gyroscope. Other researches have also conducted to prevent from falling down. K. Agrawal et al. proposed a method to choose time varying control gain to assist walking at a slope.

However, there are two problems in conventional methods. First, only human motion or around environment are considered. Nobody regarded both EWW and the user information as element for preventing fall down. It is necessary to apply measured parameter of both EWW and human to motion detecting algorithm. Second, it cost too much money to use a lot of sensors. Sensors are used to measure human information and around environment. Therefore, new motion detecting algorithm and braking system by switching command to brake safely are proposed. In this research, only one IMU sensor which can measure triple axis accelerations, Euler angles and Euler velocities are used to detect human motion.

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This sensor is not expensive, so this research can be practical. The purpose of this research is to prevent from falling down when using EWW. EWW brake by itself when EWW detects the user is likely to fall down. Timing and velocity adjustment of braking are also considered in this research.

This paper is organized as follows. In section 2, the outline of the system is introduced. Section 3 explains the modeling of EWW and handle. Section 4 explains the algorithm to detect human motion by using EWW and IMU sensor. In section 5, the controller design is introduced. In section 6, three experiments were conducted to verify the performance of proposed method. Finally, this paper is concluded in section 7.

2. Outline of the System

In this research, EWW shown in Fig. 1 is used. And Fig. 2 shows how to use EWW.

2.1 Handle Some people who use a walker cannot support their weight by themselves, because their muscle becomes weaker as they get old. So, the handle is attached to support their weight in this research. The handle also helps users to steer easily. Most of walkers have non-holonomic constraints due to prevent sharp turn. However, non-holonomic constraints make turning difficult for users. Therefore, handle command steering direction. The handle and wheels are controlled independently, because the handle is actuated to support the user not to fall down, not only to command steering motion. The handle only moves steering direction.

2.2 IMU Sensor The user attaches an IMU sensor at the red point shown in Fig. 2. IMU sensor detects user’s motion. In this research, IMU sensor detects walking state and stopping state by measuring acceleration of vertical direction. In my previous research, three IMU sensors are attached and four patterns of the user motion are detected. However, complicated algorithm is needed to judge motions of the user, therefore proposed algorithm is simpler and uses less information of the user measured by IMU sensors.

3. Modeling

EWW is composed of two parts. First one is the part of the car and the other is the handle. The modeling of the car part is shown in Fig. 3 and the handle model is shown in Fig. 4 respectively.

3.1 Kinematics of Car Part The position, posture, angle of the wheel are defined as $X = [x_0, y_0, \phi]^T$, $\theta_w = [\theta_r, \theta_l]^T$. Kinematic equation can be derived as follows using Jacob matrix $J$.

$$\dot{X} = J\dot{\theta}_w$$  \hspace{1cm} (1)

$$\begin{bmatrix} \dot{x}_0 \\ \dot{y}_0 \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{2}{R} \cos \phi & \frac{2}{R} \cos \phi \\ \frac{2}{R} \sin \phi & \frac{2}{R} \sin \phi \\ \frac{2}{R} & \frac{2}{R} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_l \end{bmatrix}$$  \hspace{1cm} (2)

3.2 Dynamics of Car Part Dynamic modeling of EWW is derived from Lagrange’s equation shown in following equation.

$$\tau_w = M_w \ddot{\theta}_w$$  \hspace{1cm} (3)

where, $M_w$ denotes inertia vector of EWW. Each parameters are composed of Eqs. (4)–(6).

$$M_w = \begin{bmatrix} mR^2 \frac{\dot{\phi}^2}{\psi^2} + J_w + \frac{Jr^2}{\psi^2} & mR^2 \frac{\dot{\phi}^2}{\psi^2} \\ mR^2 \frac{\dot{\phi}^2}{\psi^2} & mR^2 \frac{\dot{\phi}^2}{\psi^2} + J_w + \frac{Jr^2}{\psi^2} \end{bmatrix}$$  \hspace{1cm} (4)

$$\theta_w = \begin{bmatrix} \theta_r \\ \theta_l \end{bmatrix}$$  \hspace{1cm} (5)

$$\tau_w = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix}$$  \hspace{1cm} (6)

3.3 Dynamics of Handle Part In this paper, $\theta_h$, $M_h$
are the angle and the inertia of the handle. Dynamic modeling of handle part can be written as Eq. (7).

\[ \tau_h = M_h \ddot{\theta}_h \]  

\[ \text{(7)} \]

4. Proposed Algorithm to Judge User’s Motion

In this section, the method of judging user’s motion by an IMU sensor and EWW is introduced. Because patterns of human motion are various, only four motions are discussed in this research. Four motions are introduced at first, and then the motion analyses are also presented to decide the parameters which should be measured for fall-prevention. Finally, the algorithm to judge user’s motion is explained.

4.1 Considered Human Motion

The examples of falling accidents caused by walkers are as follows.

1. Moving a walker even though the user is in danger
2. Crushing by steps
3. Sharp turning

To save the user from dangerous situation, four motions those are walking, stopping, leaning, and sharp turning are considered. These motions are detected by an IMU sensor and EWW, and then prevent falling down by actuating car part and handle part of EWW.

4.2 Motion Analysis

Motion analyses were conducted to decide the parameters which should be measured for detecting human motion. Seven healthy subjects aged 22-78 years old performed two motions written as follows. During these experiments, subjects used the walker which is sold on the market.

4.2.1 Leaning Motion

In this motion analysis, the subject leaned on the walker, then stopped. Two force sensors are attached on the handle and the load toward the walker is measured during the analysis. One of the results is shown in Fig. 5. In this case, the subject started to lean on the walker at about 6 second, then stopped leaning at 12 second. The value of measured load rapidly increased and while the subject keeps leaning, the value keeps large. From the results, the load can be the parameter which detects leaning motion. Moreover, this value can be measured by observer instead of using force sensor, because the handle part is actuated.

4.2.2 Walking Motion

The subject attached an IMU sensor at chest during the analysis. Walking and stopping motions are considered. The subjects took five steps forward and stop, then took five steps forward again. Figure 6 is an example of the results. The subject started walking in straight direction at 4 second and walk 5 steps, then stopped at around 9 second. Then, subject started walking again at 12 second and stopped at around 17 second. According to the results, the value of acceleration was approximately −0.8 g during the experiment caused by gravity. When the subject walked maintaining normal upright posture, acceleration was −1.0 g. However, the subject walked with gripping handle shown in Fig. 2, the value was measured larger than −1.0 g. The acceleration of vertical direction oscillated clearly when the swing leg was landed. Therefore, this can be the parameter which detects walking and stopping motions.

4.3 Motion Detecting Algorithm

From the motion analysis, three motions, those are leaning, walking, and stopping motions are defined as Eqs. (8)-(10). In case of sudden leaning motion, it is detected by using the algorithm defined as Eq. (11). Each parameter are presented in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F )</td>
<td>Estimated load force</td>
</tr>
<tr>
<td>( a_c )</td>
<td>Chest acceleration in vertical direction</td>
</tr>
<tr>
<td>( \dot{\theta}_h )</td>
<td>Angular velocity of the handle</td>
</tr>
<tr>
<td>( k )</td>
<td>Current value</td>
</tr>
<tr>
<td>( (k-n) )</td>
<td>Value before ( n ) sampling times</td>
</tr>
<tr>
<td>( \theta_{\text{limit}} )</td>
<td>Threshold</td>
</tr>
</tbody>
</table>

In Eq. (8), change of load value (left condition) represents the beginning of leaning motion. Moreover, right condition defines leaning state. Walking motion is defined as Eq. (9), then once the subject is regarded as walking, an IMU sensor keep detect them as walking until about 0.8 second after. This time means the average time of 1 step. If the subject is not detected as leaning or walking he/she is detected as stopping. These four algorithms obviously classify four motions and according to the conditions, EWW is controlled to stop gradually and keep user safely as mentioned next section. Usually, IMU sensor is suffered from noise and off-set, therefore second-order Butterworth filter is utilized to make acceleration value of vertical direction smooth shown in Eq. (12).\[ a_c^{\text{cal}}(k) = m_1a_c^{\text{get}}(k) + m_2a_c^{\text{get}}(k-1) + m_3a_c^{\text{get}}(k-2) \]

\[ + m_4a_c^{\text{get}}(k-3) + m_5a_c^{\text{get}}(k-4) \]

where, \( a_c^{\text{cal}} \) denotes acceleration of vertical direction after calculation and \( a_c^{\text{get}} \) acceleration measured directly by IMU sensor.

5. Control System

In this section, control system with EWW and handle are
explained. First, Reaction Torque Observer (RTOB) is introduced. Then, compliance control and the decision of steering input are also introduced. The braking system in response to the user’s motion is proposed. Finally, block diagram of whole system is described.

5.1 Reaction Torque Observer (RTOB) Reaction Torque Observer (RTOB) is conducted to estimate the reaction torque of pushing force by the user. Based on the estimated torque, command velocity of EWW and the handle are generated. In case of the wheels, the motion equation of each wheels of EWW including disturbance is shown as Eq. (13).

\[
M_e \dddot{w} = \tau_w^{ref} - (\tau_w^{fric} + \ddot{\omega}_w^{dis}) \tag{13}
\]

In Eq. (13), total input disturbance is \(\tau_w^{fric} + \ddot{\omega}_w^{dis}\). Disturbance torque in the wheels is compensated by using disturbance observer (DOB). Disturbance torque caused by friction torque \(\tau_w^{fric}\) is defined as Eq. (14).

\[
\ddot{\omega}_w^{fric} = F_w + D_w \dot{\omega}_w^{res} \tag{14}
\]

\(F_w\) is coefficient of static friction and \(D_w\) is coefficient of dynamic friction. Reaction torque \(\ddot{\omega}_w^{fric}\) without \(\dddot{\omega}_w^{fric}\) can be estimated as Eq. (15).

\[
\dddot{\omega}_w^{fric} = \dddot{\omega}_w^{ref} - M_w \dot{\omega}_w^{res} - \dot{\omega}_w^{fric} \tag{15}
\]

Equation (15) can be transformed as Eq. (16) by using pseudo differentiator.

\[
\dddot{\omega}_w^{fric} = \frac{q_r}{s^2 + g_r} \left(\dddot{\omega}_w^{ref} + g_r M_w \dot{\omega}_w^{res} - \dddot{\omega}_w^{fric}\right) - g_r M_w \dot{\omega}_w^{res} \tag{16}
\]

In the equation, \(s\) is Laplace operator and \(g_r\) is cut off frequency for pseudo differentiator. Block diagram of RTOB is shown as Fig. 7. In this research, the value of cut-off frequency of low-pass filter was set small, because if the estimated value of reaction torque includes high frequency component, the motion of EWW becomes oscillative.

To transform \(\dddot{\omega}_w^{fric}\) into \(\dddot{\omega}_w^{ref}\), \(\dddot{\omega}_w^{fric}\) is transformed as Eq. (17) by using pseudo Jacobean. RTOB is also applied to the motor of handle to obtain the estimated force which command handle acceleration and velocity.

\[
\dddot{\omega}_w^{ref} = J^T \dddot{\omega}_w^{fric} \tag{17}
\]

5.2 Compliance Control Compliance control is used to generate EWW’s motion command of straight direction. The command is derived from Eq. (18).

\[
M_e \dddot{\omega}_w^{cmd} + D_e \dddot{\omega}_w^{cmd} = F_w^{reac} \tag{18}
\]

where, \(F_w^{reac}\), \(M_e\), \(D_e\) denote average value of estimated reaction force of each wheeled motors, virtual mass and damper. \(\dot{\omega}_w^{cmd}, \ddot{\omega}_w^{cmd}\) are command acceleration and velocity of straight direction. In this research, EWW is controlled based on velocity control. Adjusting \(M_e, D_e\), it is possible to generate the command synchronized to user’s force. The command in handle part is generated by Eq. (19).

\[
M_h \dddot{\omega}_h^{cmd} + D_h \dddot{\omega}_h^{cmd} = F_h^{reac} \tag{19}
\]

where, \(F_h^{reac}\), \(M_h\), \(D_h\) represent estimated reaction force of motor attached to the handle, virtual mass and damper of the handle. If the subject is detected as walking, the commands are generated based on the compliance control. Otherwise, the commands switches like following control system.

5.3 Steering Control In this subsection, steering control is introduced. The handle decides the command of steering angle of EWW. At first, weighting function \(w\) is designed as Eq. (20).

\[
w = f(\theta_h) = \begin{cases}
\frac{1}{\theta_{hi} - \theta_{lo}} & \theta_{hi} > \theta_h > \theta_{lo} \\
0 & \theta_{lo} > \theta_h > -\theta_{low} \\
-1 & \theta_{hi} > \theta_h \\
\end{cases} \tag{20}
\]

where \(\theta_h\) denotes the angle of the handle and \(\theta_{hi, lo}\) are minimum, maximum angle to rotate. These angles are designed such that user operate, then find optimal values. Command velocity in steering direction \(\dot{\phi}\) is derived from Eq. (21) based on \(w\).

\[
\dot{\phi}^{cmd} = Aw \tag{21}
\]

\(\dot{\phi}\) is the command acceleration in steering direction and\(\dot{\phi}\) is the time derivative of \(\phi\). Acceleration of wheels are calculated by Eqs. (22)/(23) by using straight and steering directions of command accelerations. Command velocity of the wheels are also derived from same equation by using \(\phi\) and \(\dot{\phi}\), instead of \(\dot{\phi}\) and \(\ddot{\phi}\).

\[
\dddot{\theta}_l = \frac{2\dddot{\omega}_l^{cmd} - \phi^{cmd} W}{2R} \tag{22}
\]

\[
\dddot{\theta}_r = \frac{2\dddot{\omega}_r^{cmd} + \phi^{cmd} W}{2R} \tag{23}
\]

Then, acceleration reference of each wheels can be obtained from Eq. (24).

\[
\dddot{\omega}_l^{ref} = K_{pl}(\dddot{\theta}_l^{cmd} - \dddot{\theta}_l^{res}) + \dddot{\theta}_l^{cmd} \tag{24}
\]

\[
\dddot{\omega}_r^{ref} = K_{pr}(\dddot{\theta}_r^{cmd} - \dddot{\theta}_r^{res}) + \dddot{\theta}_r^{cmd} \tag{25}
\]
5.4 Command Switching Based on User’s Motion

EWW is actuated by compliance control and steering control in normal walking. However, the IMU sensor and EWW detect that the user is leaning, stopping or sharply turning, the command value switches to brake EWW and handle for safety. Equation (26) generates command in straight direction.

\[ \ddot{d} = \ddot{d}_b - \ddot{d}_w \]  \hspace{2cm} (26)

\[ \ddot{d}_b = F_{\text{rec}} / M_b \] \hspace{2cm} (27)

In Eqs. (26)(27), brake command is generated when the user is detected as leaning, stopping or sharply turning. The value of brake acceleration changes by reaction force \( F_{\text{rec}} \). When the user is in danger while turning, the value of weighting function \( w \) switches to 0, shown in Eq. (28).

\[ w = 0, \dot{\phi}_{\text{cmd}} = 0 \] \hspace{2cm} (28)

Since turning angle and velocity of EWW are small for mechanical reasons, the command shown in Eq. (28) does not affect abrupt changing of motions. Therefore, EWW does not turn though the user moves the handle when the user is in danger. Command switching of handle part is shown in Eq. (29).

\[ M_{ch} \ddot{\theta}_{\text{cmd}} + D_{ch} \dot{\theta}_{\text{cmd}} + K_{ch} (\theta_{\text{cmd}} - \theta_{\text{des}}) = F_{\text{rec}} \] \hspace{2cm} (29)

Where, \( K_{ch} \) denotes virtual elastic. \( \theta_{\text{des}} \) is determined by response angle which is measured just before command switches. This elastic term means that the handle is commanded to return to the desired angle gradually. In this research, if an unexpected error causes in the RTOB computation, the command position and velocity becomes 0 then EWW will stop and remain to the point. The role of EWW is not only help user walking but also support the balance of user, therefore in case of the unexpected phenomenon in RTOB, EWW stops and support the balance of the user by staying on the point. When unexpected error occurs, the command position and velocity gradually becomes 0. After the detection, command velocity becomes \(-0.2\) rad/s until EWW stops. The value was determined by some experiment. In case of stopping motion, EWW stops gradually according to the reaction force, however if RTOB value has large error, EWW should stop regardless of the value of reaction force. Therefore, EWW stops automatically if the unexpected phenomenon in RTOB has been detected.

5.5 Block Diagram of Whole System

Figure 8 shows the block diagram of whole system. In this system, Reaction Torque Observer (RTOB) estimates reaction torque of pushing force by the user. EWW and the IMU sensor detect user’s motion, and then command values switch in response to the user’s motion. EWW brakes when the user is regarded as stopping, leaning and sharp turning. When the user walks, commands are generated based on compliance control. To trace reference values, PD controller and Disturbance Observer are used (12).

6. Experiment

In this section, experimental results are described to confirm the validity of proposed algorithm and control. In this paper, three experiments were conducted. The purpose of each experiments were to

(1) Verify that the command values switch according to proposed motion detecting algorithm and that response value trace to the command.

(2) Verify that the algorithm detects human motion.

Figure 9 shows the situations of each experiment.

6.1 Experiment A: Leaning Motion

In this experiment, part of the algorithm was evaluated. A subject attaches an IMU sensor and walked toward straight direction by using EWW. At first, the subject walked then started to lean on EWW at around 7 second. The subject kept leaning until 15 second. The value of threshold \( F_{\text{lim}} \) was 15.0 N. If command velocity generated by Eq. (24) is over 0.01 m/s backward, the command keeps 0.01 m/s for safety. Figure 10 shows estimated force of EWW. It can be seen that the value of estimated force increased sharply at 7 second, then exceeded
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6.2 Experiment B: Sharp Turning Motion In this subsection, sharp turning is considered. At first, the subject walked straight, then started to turn left side at around 3 second. At 8 second, the subject turned right side and EWW collided with the chair shown in Fig. 9 at 10 second. Due to the collision, the subject sharply moved the handle to right side and broke the balance. In this experiment, leaning and stopping detections are not considered. To detect sharp turning, the threshold \( \theta_{\text{limit}} \) was set 0.6 rad/s.

Figure 12 shows the handle velocity. It can be confirmed that command angular velocity immediately switched to brake handle motion. This means that handle was stopped, performed by proposed braking system. When the response value exceeded \( \dot{\theta}_{\text{limit}} \), the command value rapidly changed, so certain error occurred.

The results of the handle angle is shown in Fig. 13. From the result, it can be seen that the control system keeps good tracking performance. After the collision, the angle is gradually back to the value \( \theta_{\text{des}} \) which was measured just before the collision. In this experiment, the angle was \(-0.3\) rad when the subject started to turn sharply, therefore \( \theta_{\text{des}} \) written in Eq. (29) was set at \(-0.3\) rad. This means handle was commanded to return the angle at \(-0.3\) rad. It can be confirmed that the angle returned gradually to \(-0.3\) rad at the end of the experiment. Experimental result of EWW velocity in straight direction is shown in Fig. 14. In Fig. 14, EWW drove faster during 10.5–11.0 second, this was caused by sudden turning. At 11.0 second, the subject was detected as turning suddenly by handle velocity shown in Fig. 12. EWW was braked.
relative to the value of estimated reaction force.

Figure 15 shows experimental result of angular velocity of EWW in turning direction. Command velocity converted to 0 at 11.0 second. Due to the sharp change, response velocity overshot at 11.5 second, however that did not affect the safety.

6.3 Experiment C: Stopping Motion
In this experiment, stopping and walking motions are considered. The subject attached one IMU sensor on chest and the acceleration of vertical direction (Y-axis) was measured. The subject walked five steps forward, and then stopped at 6.5 second. Leaning and turning motions were not considered in the experiment. The experimental result of acceleration in vertical direction is shown in Fig. 16. Acceleration started to vary sharply at 2.5 second, this means the subject took a first step. The value sharply changed at 3.5, 4.6, 5.5 and 6.2 second. It is assumed that the subject took a step at these times. During 6.5–9.0 second, acceleration kept −0.85 g and the subject stopped as shown in Fig. 9.

Figure 17 shows EWW velocity in straight direction. EWW were moved forward until 7 second, then the subject was detected as stopping. Therefore, EWW started to brake gradually from 7.0 second and finally moved backward to return to the subject safely at 8.4 second.

7. Conclusion
The purpose of this research is to prevent from falling down when elderly person uses walker. For the purpose, motion detecting algorithm based on the measured value by using EWW and one IMU sensor were proposed. Moreover, braking system that helps assisting their body was also proposed to brake EWW and handle safely. In this paper, four motions which included walking, stopping, leaning and sharp turning were considered. To detect these four motions, reaction force which is estimated by Reaction Torque Observer (RTOB) was used and chest acceleration in vertical direction was also measured. From the experimental results, appropriate human motion detecting was confirmed and smooth braking was also confirmed.

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