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Posture estimation and human support using wearable sensors and walking-aid robot

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HIGHLIGHTS

- An omni-directional walking-aid robot is developed to assist and support the elderly.
- A wearable sensor system was designed to estimate online the human posture.
- A fall detection method by wearable sensor is obtained based on possibility theory.
- Normally the robot uses admittance control while it is braked when fall detected.
- Experiments were conducted to test the wearable sensor and walking-aid robot.

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ABSTRACT

In this paper, an omni-directional walking-aid robot is developed to assist the elderly in the daily living movements. A motion control strategy of walking-aid robot based on the observation of the human status through wearable sensors is proposed. During normal walking, the robot is controlled using a conventional admittance control scheme. When the tendency of a fall is detected, the robot will immediately react to prevent the user from falling down. The distance between the human Center of Pressure (COP) and the midpoint of the human feet is assumed to be a significant feature to detecting the fall events. When the user is in a quasi-static state or walking slowly, the COP can be approximated by the projection of Center of Gravity (COG) of the user's body. A simple and low-cost wearable sensor system is proposed to measure online the COG of the user. A limitation of the proposed wearable sensor system is that the Head–Arms–Torso (HAT) of the user is assumed to be always in upright position, which may generate measurement error. From comparison experiments with a reference optical system it is found that the measurement error is acceptable especially at the early stage of fall event. Dubois possibility theory is applied to describe the membership function of "normal walking" state. A threshold based fall detection approach is obtained from online evaluation of the walking status. Finally, experiments demonstrate the validity of the proposed strategy.

1. Introduction

The elderly people population is rapidly increasing in developing and developed countries. The increase of human average lifespan escalated the need for elderly-care technologies [1]. This increase along with a shortage of skilled caregivers presents an opportunity for robotic applications to address some of the disparities in elderly patient care. In addition, as many elderly and handicapped people suffer from lower extremity deceases, the demand for walking aid devices has increased. Robotic applications such as walking-aid robots to assist the elderly in their daily living activities and to help the elderly to regain independence and an increased quality of life will play an important role in the rehabilitative care systems of increasingly aging societies [2,3].

The current walking-aid robot systems proposed so far may be classified into two groups according to the mobility factor, i.e., the systems moving on the ground according to the motion of the subjects and the system giving effects of walking to the subjects [4]. The former system is active-type walker which is driven by servo motors [5–7]. The latter corresponds to a system

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Nomenclature

L_1, L_2, L_3: The hip, knee, ankle joints of the left human leg.
R_1, R_2, R_3: The hip, knee, ankle joints of the right human leg.
G_1, G_2, G_3, G_4, G_5: Center of Gravity (COG) points of torso, left thigh, left shank, right thigh and right shank.
s_1, s_2, s_3, s_4, s_5: Posture sensor units mounted at the torso, left thigh, left shank, right thigh and right shank.
$\{0\}, \{h\}, \{r\}, \{s_i\}$: Coordinate systems of the reference frame, human, robot and the ith sensor respectively ($i = 1, 2, \ldots, 5$).
$\{P\}$: Coordinate system that is fixed on point P and has the same orientation as $\{h\}$. Here $P \in \{L_1, L_2, L_3, R_1, R_2, R_3\}$.
$\{Ps_i\}$: Sensor coordinate system of s_i that is fixed on point P (z-axis is perpendicular to the sensor surface. x-axis is upward and parallel to the sensor surface).
X_P^Q: The coordinate value of point P represented in system $\{Q\}$.
$\mathbf{v}_R^r$: Velocity vector of robot in coordinate system $\{r\}$.
$\mathbf{f}_I^r$: Interaction force vector between human and robot.
$\mathbf{s}_i(n), \mathbf{z}_i(n)$: State and observation variables of filtering system.
$g_{xi}, g_{yi}, g_{zi}, H_{xi}, H_{yi}, H_{zi}$: Acceleration of gravity vector and geomagnetic intensity vector for sensor unit s_i.
a_{xi}, a_{yi}, a_{zi}: Outputs of accelerometer for sensor unit s_i.
h_{xi}, h_{yi}, h_{zi}: Outputs of magnetometer for sensor unit s_i.
$\omega_{xi}, \omega_{yi}, \omega_{zi}$: Outputs of gyroscopes for sensor unit s_i.
$\mathbf{w}_i(n), \mathbf{v}_i(n)$: Process noise and sensor output noise for sensor unit s_i.
C_x^y: Rotation transformation matrix which describes coordinate system $\{y\}$ relative to coordinate system $\{x\}$.
T_x^y: Homogeneous transformation matrix which describes coordinate system $\{y\}$ relative to coordinate system $\{x\}$.
θ_i, ϕ_i, ψ_i: Pitch, roll and yaw angles of the ith sensor unit ($i = 1, 2, \ldots, 5$).
$\mathbf{K}_i, \vartheta_i$: General axis and rotation angle of the ith sensor unit.
m_i: Masses of human body segment.
$P_3 : (x_{cog}, y_{cog})$: Position of human COG on the ground. It is approximately equal to COP when the walking acceleration is small.
P_1, P_2, P_4: Projection points of two feet on the ground and their midpoint.
$p(n_j), \pi(n_j)$: Probability distribution and possibility distribution of histogram over each bin n_j.
$\mu(\cdot)$: Membership degree function.

driven by servo brakes and is passive-type walker [8,9]. For the first group of walking-aid robots, force control techniques including impedance and admittance control methods are widely used in the robot motion control since they enable user-friendly Human–Robot-Interactions (HRI) that transform interaction forces from the user to the desired robot motion velocity. Huang et al. proposed an intention based admittance control for an intelligent cane robot, in which the human motion intention was identified from the interaction forces and used to guide the motion of robot [10]. Frizera-Neto et al. presented a method which offers effective cancelation of the undesired components from force data, allowing the system to extract in real-time voluntary user's navigation commands [11]. These techniques greatly improve the comfort of users when they are operating the active walkers in a "normal" case. Whereas there are not so many studies discussing the"emergency"

Fig. 1. Omni-directional walking-aid robot.

cases (e.g. fall accidents caused by stumbling or slipping). Generally, it is difficult to identify the occurrence of an "emergency" case by only using force measurement.

Falling down is a major cause of fatal injury especially for elderly and may create a serious obstruction for independent living [12]. The development of walkers should aim at improving the ability of interaction based on the data from the environment, particularly the ability of fall detection and fall prevention for the user. Hirata designed a fall prevention motion control strategy for a intelligent passive-type walker [13]. In his study, the user state was estimated by a couple of laser ranger finders that predict the occurrence of falling down. Huang et al. proposed a cane-type walking-aid robot which is controlled based on the estimation of the user's walking intention [10]. A fall detection method is also utilized in the cane robot by combining the sensory data of an omni-directional camera and a laser ranger finder[14]. It should be noted that a laser ranger finder is normally expensive and the process of vision information is time-consuming. Considering the cost and real-time requirement in a practical system, wearable sensors might be a better choice in the fall detection.

Wearable device based fall detection method mainly relies on various sensors to detect the motion and location of the body of the user [15]. To analyze the output of a waist accelerometer, researchers use variance and average, kurtosis and skewness statistics to realize eight kinds of activities such as walking, climbing, running, standing, sitting, and lying prone [16]. Masaki et al. [17] classified the output of waist accelerometers during human climbing motion using fractal analysis method based on a wavelet transform process. Wang et al. [18] obtained data from a 3-axis waist accelerometer, then used 33 different time-domain characteristics to classify the five different types of gaits characteristic of walking on flat ground, uphill, downhill, upstairs and downstairs. In this paper, the force sensors of the robotic device are used to ensure motion control while the wearable sensors are used to monitor user's gait and detect the occurrence of falling down.

First, the walking-aid robot and its motion control algorithm are introduced in Section 2. The framework of the fall detection system based on observing human status by wearable sensors is presented in Section 3. Having such data, the experimental results of proposed algorithm are shown in Section 4. The final section concludes the paper and gives further perspectives.

2. Walking-aid robot

The prototype of an omni-directional walking-aid robot is illustrated in Fig. 1. The robot consists of an omni-directional base, a support frame, a motion controller and a battery system.

The omni-directional mobile base comprises three commercial omni-wheels and actuators. Several passive casters are also mounted on the base to widen the support area so as to enhance the stability. Coordinate systems are depicted in Fig. 2. Three one-dimensional force sensors are used to measure the interaction forces between the robot and the operator. Both the forward