Advanced Motion Control for Wheelchair Based on Environment Quarrier

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An intelligent wheelchair for adaptation to unknown and/or unstructured environment is developed in this paper. In the motion control under open environment, it is necessary for a robot to adapt to interference from other systems and unknown environment. Since both of the human force and the external force from the environment are applied to a robot as a disturbance, it is difficult for a robot to decompose them into each mode.

In order to solve the above problem, a novel force sensing method named “Environment Quarrier” is proposed in this paper. Two same types of robots are required and they are controlled in the same position, velocity and acceleration by bilateral control. One robot is in contact motion and the other is unconstrained. The gravity and the friction effects are identified by the disturbance observer. The purity of external force is obtained by subtracting the disturbance torque in the unconstrained robot from the constrained one.

The proposed method is applied for a power-assist wheelchair. An operationality of a human and adaptability to the environment are improved. Sensor-less force control based on the environment quarrier is one of the fundamental techniques for evolution of human-cooperative robots. The experimental results show viability of the proposed method.

Keywords: motion control, disturbance observer, acceleration control, wheelchair, haptics, human-robot interaction, environment quarrier

1. Introduction

In Japan, a declining birth rate and aging population are increasing. A robot will then be expected to play the role of a human’s partner. Generally, a human recognizes environment and plans his trajectory without collision with obstacles. Since a human can make a synthetic judgment to various environmental situations based on rich knowledge and experience, he can do dexterous work with flexibility. A human may get tired by doing the work which needs concentration and muscle force for a long time, and an error may increase. Moreover, a human becomes bored with the monotonous work.

On the other hand, a robot generates a controlled force more than human. However, it is difficult for a robot to work autonomously recognizing an environment. Works by robots under the complicated environment where advance modeling is difficult is off from practical use. Thus, a human will obtain convenient and efficient systems by considering the characteristics of both sides of a human and a robot. The best combination of human ability and robot capacity should be considered.

For well cooperation with a robot, a human can touch it. A robot should have a haptic ability. In the future, a robot should have the ability of physical cooperation with a human. It means that a robot should control the interaction of force. Once such kind of ability is installed, then it becomes cooperative with humans. Cooperation of a human and robots is realized through force control.

In recent years, power-assist wheelchairs have been researched for elderly and/or handicapped people because a support system for a care worker is demanded. A human-robot-environment integrated system is a key technology for advanced robot motion control. Overview of the human-robot-environment system is shown in Fig. 1. Since both of the human force and the external force from the environment are applied to a robot as a disturbance, it is difficult for a robot to decompose them into each mode. In other words, a quarry process is required for a human-robot-environment interaction. The quarry process means extracting only the information which a robot adapts to from the environmental information with infinite mode.

Power-assist control of a wheelchair in a slope environment is an important problem for developing wheelchairs.

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since it is difficult to decompose a human force and the external force from the slope environment. There are two approaches for solving the above problem. One of the solutions is sensor fusion\(^{(5,6)}\). In the conventional force control, much research has detected an external force by using force sensors. However, the external force is detected only at the position where the force sensors are implemented\(^{(7)}\). It will be a problem for a complicated environment. A gyroscope and an inclination sensor can detect the slope angle; however, a system becomes complicated. Moreover, the problem of the cost by use of sensors is negligible. Sensor-less adaptive methods to dynamic environment have been desired.

A disturbance observer\(^{(8)}\) is the other solution for observation of the external force. The disturbance observer compensates whole disturbance torque including the gravity torque, friction torque, torque ripple, external force, and so on. It is necessary to identify the gravity and the friction torque for estimating the reaction torque from the environment\(^{(9)}\). However, it is hard to identify these effects since the gravity torque is changed due to variation in the posture of a robot, and the friction effect is a nonlinear disturbance.

In order to solve the problem, a novel force sensing method named “Environment Quarrier”\(^{(10)}\) is proposed in this paper. Two same types of robots are required and they are controlled in the same position, velocity and acceleration by bilateral control. One robot is in contact motion and the other is unconstrained. The gravity and the friction effects are identified by the disturbance observer. The purity of external force is abstracted by subtracting the disturbance torque in the unconstrained robot from the constrained one.

The proposed method is applied for a power-assist wheelchair. When the environmental conditions are changed from flat to slope, the desired operability is attained by the environment quarrier. Furthermore, even if the passenger is changed, the gravity compensation is attained online. As a result, adaptation to unknown environment is improved without change of the control system. The environment quarrier is one of the fundamental techniques for evolution of human-cooperative robots.

This paper is organized as follows. In the following section, a modeling of the wheelchair robot used in this paper is described. The disturbance observer is shown in Section 3. In Section 4, the environment quarrier is proposed as a novel force sensing method. Section 5 shows a control design of a power-assist wheelchair based on the environment quarrier. In Section 6, experimental results are presented with a thorough comparative discussion. At the last section, this paper is summarized.

### 2. Modeling of Wheelchair Robot

The robot model used in this paper is shown in Fig. 2\(^{(11)}\). The model parameters are described as follows:

\[
\begin{align*}
  x_0 & : x \text{ coordinate of the wheelchair base point with respect to the world coordinate system} \\
  y_0 & : y \text{ coordinate of the wheelchair base point with respect to the world coordinate system} \\
  \phi & : \text{Robot’s direction angle}
\end{align*}
\]

\[
\begin{align*}
  R & : \text{Radius of driving wheels} \\
  W & : \text{Robot’s tread} \\
  \theta_r & : \text{Rotation angle of right wheel} \\
  \theta_l & : \text{Rotation angle of left wheel}
\end{align*}
\]

#### 2.1 Dynamics in Joint Space

The position of the center of gravity point of a wheelchair robot is on \(P_0\) shown in Fig. 2. At this time, movement energy function \(K\) is defined by (1)

\[
K = \frac{1}{2} M \left( \frac{R}{2} (\dot{\theta}_r + \dot{\theta}_l) \right)^2 + \frac{1}{2} J_r \left( \frac{R}{W} (\dot{\theta}_r - \dot{\theta}_l) \right)^2 + \frac{1}{2} J (\dot{\theta}_r^2 + \dot{\theta}_l^2).
\]

where

\[
\begin{align*}
  M & : \text{Mass of the wheelchair robot} \\
  J & : \text{Inertia of the wheelchair robot with respect to a vertical axis through } P_0 \\
  J_w & : \text{Inertia of each driving wheel and the motor rotor with respect to the wheel axis}
\end{align*}
\]

The first term is the translational movement energy, the second term is the rotation energy of the vehicle, and the third term is the rotation energy of the wheel. The robot’s dynamics are defined by (2) by solving the Lagrange equation from (1)

\[
\begin{bmatrix}
  \tau_r \\
  \tau_l \\
\end{bmatrix} = M \dot{\theta} + M \ddot{\theta} = \begin{bmatrix}
  M R \dddot{x} + J \dddot{\theta} & \dddot{y} \\
  \dddot{y} & -J \dddot{\theta}
\end{bmatrix}
\]

\[
M = R^2 \left[ \begin{bmatrix}
  M & J \\
  J & M
\end{bmatrix} + \begin{bmatrix}
  J \theta_r^2 + J \theta_l^2 \\
  J \theta_r^2 + J \theta_l^2
\end{bmatrix} \right]
\]

where \(M\) is called an equivalent inertia matrix and \(\tau_{r,l}\) denote right/left motor torques, respectively.

### 3. Disturbance Observer

A disturbance observer\(^{(8)}\) is designed to cancel the disturbance torque as quickly as possible. The estimated disturbance torque is obtained from the velocity response \(\dot{\theta}\) and the current reference \(\dot{\theta}_{ref}\) as shown in Fig. 3. The disturbance torque \(\tau_{dist}\) is represented as (4)
\[
\tau_{\text{dis}} = \tau_l + \Delta J\ddot{\theta} - \Delta K_t I_{\text{ref}}
\]
\[
= \tau_{\text{int}} + \tau_{\text{ext}} + F + D\dot{\theta}
\]
\[
+ (J - J_n)\ddot{\theta} + (K_{in} - K_t) I_{\text{ref}}
\]
where

\( J \) : Motor inertia
\( \theta \) : Angle of the motor
\( \tau_l \) : Load torque
\( \tau_{\text{int}} \) : Internal torque
\( \tau_{\text{ext}} \) : External torque
\( F \) : Coulomb friction
\( D\dot{\theta} \) : Viscous friction
\( K_t \) : Torque coefficient

Equation (5) shows that the disturbance torque is estimated through the first-order low-pass filter

\[
\hat{\tau}_{\text{dis}} = \frac{g_{\text{dis}}}{s + g_{\text{dis}}} \tau_{\text{dis}}
\]
where \( g_{\text{dis}} \) denotes the cut-off frequency of the first-order low-pass filter. The disturbance torque estimated by (5) is used for a realization of robust motion control. And a robust motion controller makes a motion system to be an acceleration control system. In the actual application, the estimated disturbance torque is effective for not only the disturbance compensation but also the parameter identification.

4. Environment Quarrier

A novel force sensing method based on the environment quarrier\(^{10}\) is proposed in this paper. Two same types of robots are required and they are controlled in the same position, velocity and acceleration by bilateral control. One robot is in contact motion and the other is unconstrained. The gravity and friction effects are identified by the disturbance observer. The disturbance torque except an external force is identified by the dummy robot on-line. The purity of external force is abstracted by subtracting the disturbance torque in the unconstrained robot from the constrained one. Since the environment quarrier does not need parameter identification, it is very easy to implement it in multi-link manipulators.

Overview of the environment quarrier is shown in Fig. 4.

When the robot 1 is in contact motion and the robot 2 is unconstrained, each disturbance torque estimated by the disturbance observer is represented as follows,

\[
\tau_{\text{dis}1} = \tau_{\text{env}} + \tau_{g1} + \tau_{f1} + \tau_{\text{int}}
\]
\[
\tau_{\text{dis}2} = 0 + \tau_{g2} + \tau_{f2} + \tau_{\text{int}}
\]
where

\( \tau_{\text{dis}} \) : Disturbance torque
\( \tau_{g} \) : Gravity torque
\( \tau_{f} \) : Friction torque
\( \tau_{\text{int}} \) : Interactive torque
\( \tau_{\text{env}} \) : External torque.

When the robot 1 and the robot 2 have the same structure and the same position, velocity and acceleration are controlled by bilateral control, all of the gravity, friction and interactive effects have the same value

\[
\tau_{g1} = \tau_{g2}
\]
\[
\tau_{f1} = \tau_{f2}
\]
\[
\tau_{\text{int}} = \tau_{\text{int2}}
\]
Only the external force is obtained by subtracting the disturbance torque in the unconstrained robot 2 from the one in constrained robot 1

\[
\tau_{\text{env}} = \tau_{\text{dis}1} - \tau_{\text{dis}2}
\]
Thus, the position command is expressed in the common mode of two robots. On the other hand, the force command is
expressed in the differential mode. The commands of the environment quarrier are represented in the matrix form using the second-order Hadamard matrix $H_2$

$$
\text{diag}\left[ \begin{array}{cc}
\theta_1^{\text{res}} & \theta_2^{\text{res}} \\
\tau_{\text{dis}1} & \tau_{\text{dis}2}
\end{array} \right] H_2
$$

where

$$
H_2 = \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix}
$$

A block diagram of the environment quarrier is shown in Fig. 5. $K_p$ and $K_v$ denote the position control gain and the velocity control gain, respectively. $G_r$ denotes the gear ratio of a robot joint. The disturbance observer can observe whole disturbance as acceleration information. Acceleration information from the environment is obtained by using the environment quarrier. The environment quarrier is used effectively not only as a force sensor but also as an acceleration sensor.

5. Controller Design

In order to solve the problem of control system for a power-assist wheelchair in slope environment, the environment quarrier is applied for a wheelchair. In this section, the proposed power-assist control of a wheelchair based on the environment quarrier is described. This paper assumes that only the right wheel is operated by a human and the left wheel is not inputted. Such a system is effective for people with hemiplegia on the assumption that the two wheels are in the same environment. If human operates the left wheel, since the environment quarrier observes the external torque in the differential mode of the two wheels, the force of a direction contrary to the direction where human applied force comes back.

A wheelchair robot based on the environment quarrier is shown in Fig. 7. The right and the left wheels of the wheelchair robot are controlled independently. Each wheel is controlled in the same position, velocity and acceleration by bilateral control. The position command of each wheel is described as follows,

$$
\dot{\theta}_\text{cmd} = \frac{1}{2}(\theta_1^{\text{res}} + \theta_2^{\text{res}}).
$$

In order to provide a robot with flexibility, a human force observed by the environment quarrier $\hat{\tau}_\text{hum}$ is fed back as an acceleration command. A total acceleration command of each wheel is described as follows,

$$
\ddot{\theta}_\text{ref} = (K_p + K_v s)(\theta^{\text{cmd}} - \theta^{\text{res}}) - \frac{\hat{\tau}_\text{hum}}{M_c}
$$

$$
\ddot{\theta}_l = (K_p + K_v s)(\theta^{\text{cmd}} - \theta^{\text{res}}) - \frac{\hat{\tau}_\text{hum}}{M_c}
$$

where $K_p$ denotes the position control gain and $K_v$ denotes the velocity control gain. $M_c$ denotes a compliance characteristic, i.e. the virtual mass of the wheelchair. According
to the above equations, the position regulator and the force servoing are integrated in the acceleration dimension.

Equation (15) and (16) are the final result. The acceleration commands are realized by the robust control system based on the disturbance observer. The acceleration commands are transformed to torque commands by motor inertia. A total control system is shown in Fig. 6. In this case, since one motor is implemented in each wheel, one degree-of-freedom (DOF) motion, i.e. translational direction mode is attained. Since a motion of a moving object is made up of a majority of translational motion, the assumption of this paper is appropriate. Rotatory motion is obtained by adding another function. If two motors are implemented in each wheel, two DOF motion including rotatory motion is attained.

6. Experiments

The experimental results that a human operates a wheelchair robot are shown. The experimental setup is shown in Fig. 8. Signal flow of the experimental system is shown in Fig. 9. Control software is written in C language under MS-DOS. The sampling time is 1 ms. The parameters used in the experiments are shown in Table 1.

The experiments are conducted on the following conditions.

- Flat environment—human pushes and pulls wheel twice.
- Slope environment—angle of gradient is set to 5 degrees.

The experimental results where the wheelchair robot is operated in the flat environment are shown in Fig. 10. From Fig. 10(a), the force responses observed by the disturbance observer have noise due to gear engagement. Since the force is detected in the differential mode of two wheels, it turns out that the noise rejection is achieved from Fig. 10(b). By using the environment quarrier, only the human force is observed without a complicated identification. It turns out that the estimated reaction force is 0 correctly when a human does not apply his force to the robot. The wheelchair robot decomposes the friction effect and the human force by the environment quarrier. Since the friction effects which have nonlinearity are compensated, operability is improved. The position error between two wheels is always under 0.020 rad from Fig. 10(d).

The experimental results where the wheelchair robot is operated in the slope environment are shown in Fig. 11. From Fig. 11(a), the force responses due to the gravity effects are observed around 10~15 Nm. Since the gravity compensation is attained by the environment quarrier, the robot stays in halfway up a slope without sensors such as inclination sensor from Fig. 11(c). The position error between two wheels is always under 0.012 rad from Fig. 11(d).

When the environmental conditions are changed from flat to slope, the desired operability is attained. It is difficult to compare the operability with the other method; however, intuitive motion is attained through the experiments since only the human force is applied for the wheelchair and the other disturbance torque is compensated. Especially, since the friction affects the operability, on-line compensation by the environment quarrier is very effective for human operation. The environment quarrier will be a basic technology for haptic devices.

7. Conclusions

An intelligent wheelchair for adaptation to unknown and/or unstructured environment was developed in this paper. A quarry process is a key technology for a human-robot-environment interaction. The quarry process means extracting only the information which a robot adapt to from the environmental information with infinite mode. A novel force sensing method by the environment quarrier was proposed in this paper. The purity of external force was quarried by subtracting the disturbance torque in the unconstrained robot from the operated one.

Since the external force was detected in the differential mode of two systems, the sensing noise was removable and wide bandwidth of force information is obtained by setting the cut-off frequency of the disturbance observer. Since the environment quarrier does not need parameter identification, it is very easy to implement for multi-link manipulators.

The proposed method was applied for a power-assist
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Fig. 10. Experimental results of flat environment

Fig. 11. Experimental results of slope environment
wheelchair. When the environmental conditions were changed from flat to slope, the desired operationality was attained by the environment quarrier. As a result, an operationality of a human and adaptability to the environment were improved. The experimental results showed viability of the proposed method. Force sensing method based on the environment quarrier will be a fundamental technique for evolution of human cooperative robots.

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