A Mobile Robot Platform Using Double-Wheel Caster Units Based on the Servo Brake Control

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論文内容要旨

Robots of the future are expected to enter daily life, such as in domestic and medical/welfare environments. In Japan, especially, the issue of a small labor force is problematic because of an aging society with a decreasing birth rate. Robot technologies are expected to be one solution to such problems. In human living environments, robots are expected to support a human's activity and work in cooperation with humans. In this scenario, physical human-robot interaction (pHRI) will remain a major challenge. Until now, different pHRI systems have been introduced and most of these robots use servo motors to control their motion or to support human motion.

We define this type of robot system as an active-type robot. Active-type robots are very useful for performing several functions because they can support some part of a human's motion energy and move actively. In addition, with respect to intuitive interaction with a human user and the ability to effectively contribute to a task, active-type robots have strong potential to proactively assist a human user. However, unintentional motion of the robot, which cannot be appropriately controlled by servo motors, could potentially pose a safety threat; i.e., a robot's active behavior based on an unintentional situation or a malfunction of the robot could pose a danger. As a result, in pHRI, user safety is an important issue from a practical point of view.

The concept of passive robotics has been proposed from a safety point of view. In this concept, a system does not use servomotors to generate a driving force and moves passively in response to external forces/moments. We define this type of robot system as a passive type system. The passive-type systems are intrinsically safe because they cannot move unintentionally in the absence of a driving force. In general, a pHRI system is physically coupled to the human user, who communicates with the system through interactive force. Therefore, the pHRI system is assumed to continuously receive

external forces applied by the human user. In the concept of passive robotics, pHRI systems are designed to achieve both high safety and high performance by controlling the external force applied by the human user.

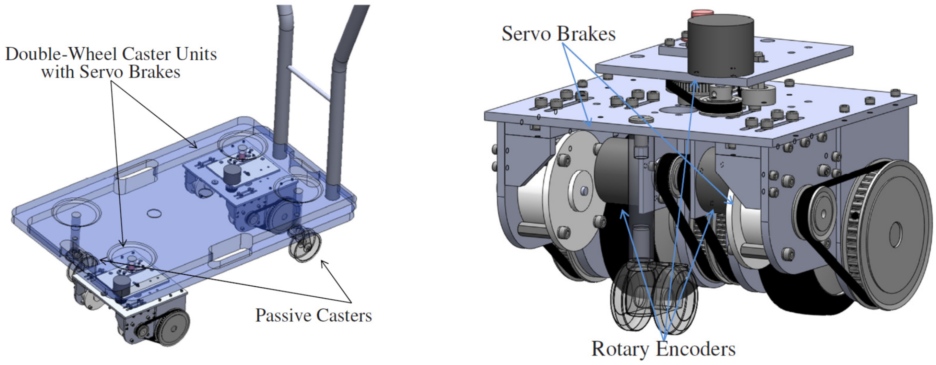
Because passive robotics ensure the safety of the user, such systems can be applied in human moving support systems that require strong safety margins, such as walkers, baby carriages, and stretchers. In addition, in some pHRI systems, such as object handling systems and haptic devices, the active devices are not indispensable. For example, a typical human can move a heavy object weighing less than 200–300 kg with a cart without active support. With respect to haptic devices, the motion of the human can be changed or restricted through the use of dissipative devices such as servo brakes and the interactive force can be haptically displayed.

In general, passive-type systems are categorized into two main types: steering-control-type and dissipative-type systems. The steering-control-type systems control or steer the direction of the motion by using servo motors. For example, an object handling system called Cobot was developed consisting of non-offset casters steered by servo motors; this system contains no servo motors for driving it. Cobot guides the object by changing the direction of the robot's motion through control of the steering angles.

Several types of dissipative-type of passive systems have also been proposed. These systems consist of servo brakes or clutches that can only dissipate energy from the system. We have developed a passive intelligent walker called RT Walker to support people with disabilities and the elderly with walking. The RT Walker contains servo brakes attached to wheels. The walker controls the servo brakes to perform several functions, such as navigation, gravity compensation on a slope, and collision avoidance, without the use of servo motors.

In addition, dissipative-type robots can dissipate motion energy, e.g., to assist a human by reducing the robot's movement speed. From a safety point of view, especially in the case of handling a heavy object or transporting a human, the robot capability to effectively reduce the motion speed is important. Hence, these dissipative passive systems are suitable for handling a heavy object or dissipating human motion energy.

However, although the passive systems controlled by servo brakes can both ensure safety and provide the desired assistance, they sometimes cannot generate sufficient force to achieve the desired motion. In this dissertation, we focus on a dissipative-type mobile robot platform that provides high safety and high mobility, but with the added advantage that it can generate sufficient force to achieve the desired motion. With respect to mobility, casters are widely used in the real world because they have several characteristics that make them suitable as moving bases: one of their most important features is their ability to move in all directions. Second, when we transport an object using a moving base consisting of casters, we can arbitrarily choose the number and positions of casters on the basis of the object's weight or shape. In contrast, control of a system with casters is challenging because of their complex structure. In this dissertation, we address the problem of combining the servo brake control and the caster for a new type passive mobile platform, which could enable us to achieve high safety and



(a) Model of Cart (b) Double-Wheel Caster Units with Servo Brakes

Fig. 1: A Mobile Robot Platform using Double-Wheel Caster Units with Servo Brakes

high mobility while simultaneously providing assistive functions in a moving system that deals with large, long, or complex-shaped objects, including human beings.

This dissertation consists of six chapters.

In Chapter 2, we first introduce the general motion control algorithm for a passive mobile robot controlled by servo brakes. In addition, on the basis of the proposed algorithm, we specify the problems encountered, i.e., the necessary requirements, in the development of a mobile robot platform that uses casters with servo brakes and in controlling its motion.

In Chapter 3, we analyze the feasible braking force/moment set of our passive mobile robot that uses casters with servo brakes. In passive systems consisting of wheels with servo brakes, a feasible braking force/moment set is derived on the basis of the characteristics of the servo brakes. We can control the passive systems on the basis of the feasible braking force/moment set. First, we focus on the relationship between the motion control of the passive mobile robot and the feasible braking force/moment set. In this analysis, we indicate how the feasible braking force/moment set should be generated for the motion control of the passive mobile robot. Second, we focus on two typical types of casters: a single-wheel caster and a double-wheel caster. Because of the difference between the two casters' structures, the characteristics of the resultant feasible braking force/moment set also differ. On the basis of our analysis, we conclude that the double-wheel casters are suitable for controlling the motion of the mobile robot platform via servo brakes.

In Chapter 4, on the basis of the analysis explained in Chapter 3, we develop a mobile robot platform that uses double-wheel casters with servo brakes. As an example of an omnidirectional mobile platform, we focus on a cart with multiple casters and develop a double-wheel caster unit that can be controlled using servo brakes, as shown in Fig. 1. The number and positions of caster units are user-selectable most appropriate to the weight or shape of the object, as shown in Fig. 2. Second, we explain the characteristics and kinematics of the cart with multiple double-wheel caster units. When a user-controlled mobile robot platform is constructed using casters, the geometrical relationships among the caster units, i.e., the poses of the casters, are essential for odometry and control. In our system, however, after attaching the caster units to the mobile base, the user is

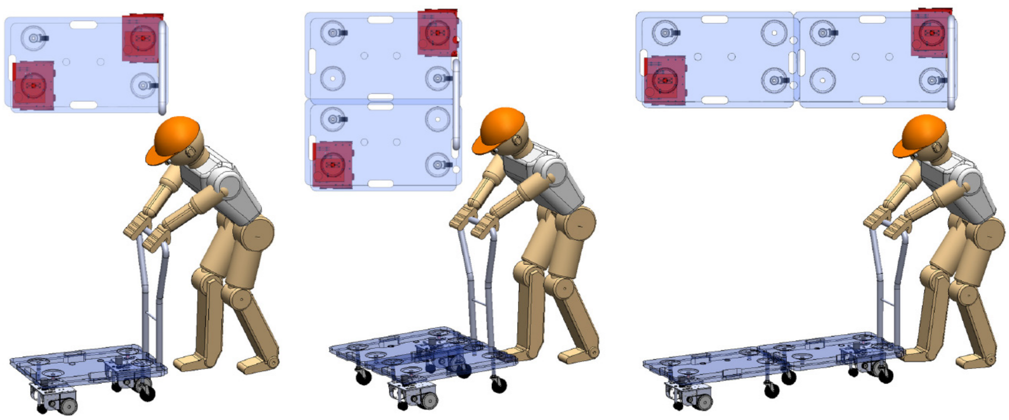


Fig. 2: The size of a base is selectable according to the user's intend.

required to input the geometrical relationships into the controller before deploying the robot. This process increases the workload of the user. Therefore, we finally propose a method for estimating the geometrical relationship among the attachment points of the caster units on the basis of velocity information. The results of the simulation and experiment verify that the proposed method is valid.

In Chapter 5, we consider the motion control algorithm for the proposed mobile robot platform. On the basis of the feasible braking force/moment set, we achieve the desired motion, e.g., to assist a human by a combination of the braking force/moment and part of the force/moment applied by the human. In this approach, we derive the braking force/moment to minimize the dissipation of the motion energy, i.e., to minimize the burden of the human. In our previous research, we determined this braking force/moment on the basis of a geometric analysis of the relationship between the feasible braking force/moment set and the force/moment applied by the human. However, when we control the 3-degreesof-freedom (DoF) motion of the robot in two-dimensional (2D) space via multiple servo brakes, the feasible braking force/moment set is dramatically and intricately changed according to the motion state of the robot. Therefore, a determination of the appropriate braking force/moment required to minimize the burden of the human on the basis of the geometric analysis is difficult. To derive the appropriate braking force/moment on the basis of the proposed algorithm, we propose a generalized approach for deriving the appropriate braking force/moment to minimize the burden on a human without geometric analysis. The validity of the proposed method is illustrated by computer simulations. Moreover, on the basis of the proposed method, we propose two functions as examples to achieve support of a human, i.e., path tracking and gravity compensation on a slope, which are experimentally validated using a cart with double-wheel caster units.

Finally, in Chapter 6, we summarize the results presented in this dissertation.

論文審査結果の要旨

ロボットの知能化が進み，人と共存するロボットの実現が期待されているが，通常のロボットは，アクチュエータによって駆動されるため，システムの安全性を確保することは容易ではなく，いまだその実用化が限られているのが現状である。 本研究では，利用者が加える力によって駆動され，その安全性確保が容易な移動ロボットプラットフォームの知能化を目的として，サーボブレーキを用いた移動ロボットプラットフォームの運動制御システムを提案するもので，全編6章からなる。

第1章は序論であり，本研究の背景，目的および構成について述べている。

第2章は，利用者が加える力によって駆動され，車輪に取り付けられたサーボブレーキの出力トルクによってその運動を制御することができる，移動ロボットプラットフォームの新しい概念を提案している。これは，重要な成果である。

第3章では，サーボブレーキ付きキャスターを用いた移動プラットフォームの，一般的な運動制御手法を提案している。サーボブレーキ付きキャスターによって発生できる力・モーメントと，プラットフォームの運動制御問題との関係を考察するとともに，単輪キャスターとサーボブレーキ付き双輪キャスターによって，プラットフォームに発生できるブレーキカ・モーメントを導出し，提案するシステムの場合には，双輪キャスターのほうが有効であることを示している。これは，有用な知見である。

第4章では，新たにサーボブレーキ付き双輪キャスターを4台用いた移動ロボットプラットフォームを提案し，プロトタイプシステムを設計／試作し，その運動学的解析を行ない，制御の際に必要となる，プラットフォームの幾何学的パラメータのリアルタイム推定方法を提案している。これは，重要な結果である。

第5章は，前章で提案した移動プラットフォームの運動制御系を設計し，プラットフォームへの制御入力を，それぞれのサーボブレーキ付き双輪キャスターを用いてどのように発生するかについて議論し，線形最適化問題として定式化し，各ブレーキが発生すべきブレーキトルクを導出し，具体的な制御系構築法を提案している。さらに，様々な場面を想定した実験を行い，提案するプラットフォームと制御システムの有効性を示している。これは，プラットフォームの実用化に対する，重要な成果である。

第6章は結論である。

以上要するに本論文は， 利用者が加える力によって駆動される移動ロボットプラットフォームの知能化を目的として，サーボブレーキを用いた移動ロボットプラットフォームの運動制御システムを提案し，サーボブレーキのブレーキトルクによって，プラットフォームの運動制御が可能なことを示すもので，バイオロボティクスおよび機械工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。