Control of Walking Support Systems Based on Variable Center of Rotation

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論文内容要旨

The population of elderly people is rapidly increasing and it is estimated that this will continue to increase in the future. In Japan, the current elderly population is about 20 percent of its total population. This elderly percentage will continue to increase to 35 percent by 2050. The increasing population of elderly, existence of several elderly problems, and the lack of caregivers lead to the development of devices and applications that will support or assist elderly in their daily activities. One problem of the elderly is mobility and this cannot be treated medically or surgically. Mobility aids such as conventional walkers are commonly used to address elderly mobility problem. It provides walking stability to the user, but there are situations that the aforementioned device is inadequate for elderly use. It also requires the user to have good judgment, vision, and endurance, which are difficult to satisfy for an aging user. The increasing technology in robotics and the need to augment some functions to the conventional walkers lead to the development of robotic walking support system.

The current researches on robotic walking support system are focused in augmenting high-level functions such as obstacle avoidance, guidance, and health monitoring. These high-level functions are meaningless if the user cannot properly control the walking support system. Although several researches have been reported on robotic walking support system, but studies in adapting user characteristics had not been reported. It is the main objective of this study to develop a new control approach, which will try to adapt user's controlling characteristics. The control approach aims to help users who have difficulties in controlling their walker. In addition, training is normally done prior to the actual usage of conventional walker. This is done not only to conventional walker but also to other assistive devices. This implies that repetitive training will be performed until the user is proficient in using the new device. In this approach, the user tries to model and adapt the assistive device. Designing a system that can change its characteristics to adapt user's controlling ability will be of great interest and it will also address the changing controlling characteristics of a user due to aging.

This study proposes a new control approach for a robotic walking support system to adapt user's controlling characteristics. The control approach changes the kinematic structure of the walking support system and this will be implemented by varying the center of rotation. One advantage of varying the center of rotation to adapt the user's controlling characteristics is that the maneuverability of the system only changes when there is a user intention, which will be represented by applied force/torque. The new control approach aims to help users who have difficulties in controlling their walking support system.

Chapter 1 discusses the motivation and objective of the study. We present the literature review on mobile base platform, human-robotic walking support system interface, and existing robotic walkers. In chapter 2, the hardware and system description of a new robotic walking support system referred as "Walking Helper" is discussed. There are two versions of walking support system used in this study namely, "Walking Helper I" and "Walking Helper II". The system's architecture and control algorithm of the two robotic walking support systems are identical. However, these systems differ in the mobile base geometric structure and force/torque sensing implementation.

"Walking Helper I" is an active type of walking support system. It has an omnidirectional mobile base, support frame, computer system, analog to digital and digital to analog converters, and wireless Ethernet module. "Walking Helper I" is also installed with a force/torque sensor, which is used to measure user's intentions in the form of applied force/torque. The force/torque sensor data is used to derive the command signals to the robotic walking support system's motion controller. The omnidirectional mobile base of "Walking Helper I" is implemented using four Mecanum wheels driven by a DC motor with an encoder. The mobile base also handles the weight of the sensors and the body frame, which supports the user. Due to the wheel structure, it is possible to implement an omnidirectional mobile base even though the wheel positioning is a car-like. The mobile base kinematic equations are derived based on an arbitrary point called center of rotation.

"Walking Helper II" is an enhancement of the first version and this is shown in Fig. 1. This system is installed with a body force/torque sensor for safety purposes and for its motion control algorithm. The general motion control algorithm of the walking support system is based on imposed apparent dynamics. The applied force/torque is fed to the apparent dynamics to get the support system's desired velocity and this is fed to the motion controller for regulation. The force/torque sensor is installed near the mobile base actuators. The approach in installing the force/torque sensor near the actuators leads to a larger control bandwidth since this creates a small amount of delay between sensing and actuating. The new robotic walking support system is also installed with several sensors such as laser range finders and this is used to implement the high-level functions of the system.

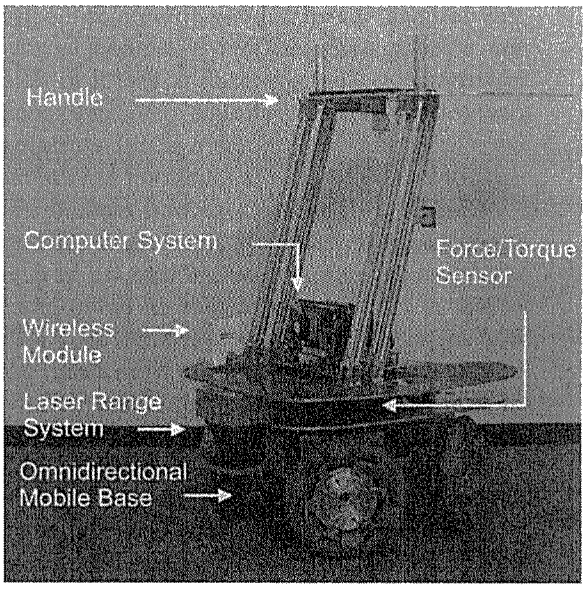

Fig. 1 "Walking Helper II"

Chapter 3 discusses the concept of relocated center of rotation. We define and differentiate center of rotation and instantaneous center of rotation. These points are not the same based on user's intention and walking support system normal operation. Force/torque transformation is also presented and this determines the new force/torque of the system at the new center of rotation. The desired velocity at the new center of rotation is taken based on the imposed apparent dynamics. This is followed by velocity transformation where the desired velocity at the new center of rotation is transformed back to the original center of rotation. In addition, we present the general control framework of relocated center of rotation. This starts from application of user's intention to wheel velocity regulation. We also present the trajectory evaluation using new center of rotations. We try to evaluate the effect of relocating the center of rotation to the system's maneuverability and this is implemented by allowing the user to use the walking support system with relocated center of rotation. In the evaluation, the user only applies force along X-axis. In a non-relocated center of rotation situation, the support system will only have a translational motion along X-axis. We show that with relocated center of rotation, the system can have both translational and rotational motion.

Chapter 4 discusses the process in determining new center of rotation. We have a training stage to evaluate and adapt user's controlling characteristics. This is implemented by allowing the user to follow some training paths. In the event large path error occurs, a learning algorithm is used to vary the center of rotation of the support system until the user can successfully follow the training path. The above method describes an online approach in determining a new center of rotation for a certain training path and the training block diagram is shown in Fig. 2. The relationship between the user intent in the form of applied force/torque and new center of rotation is taken by considering several training paths. This relationship is used to implement a variable center of rotation control of the robotic walking support system. In the implementation of the variable center of rotation, the new center of rotation is a function of the applied torque. This is done since the applied torque is highly correlated to the heading angle of the system.

The mean of the absolute error (MAE) is used as a criterion to evaluate the new center of rotation for a certain training path. It represents the average deviation of the walking support system in following a training path or desired path such as S-path based on user's controlling characteristics. The MAE is taken by allowing the user to follow a training path or S-path using the original center of rotation, which is located at the origin of the walking support system coordinate and the new center of rotation. In addition, environment-based training is also presented as an alternative method in determining new center of rotation. This training approach use environment information such as position and orientation of the support system with respect to walls, edges, and other landmarks.

Environment-based training eliminates the process in preparing the training path but this is limited to the structure of the environment. This approach is useful in determining the new center of rotation for straight path and specific curves. In the current implementation, there is still a training stage and not all environments are used as a training environment.

Chapter 5 discusses a second method in determining new center of rotation and it is based on an offline approach. This is used to reduce the number of training in determining the new center of rotations and it uses an environment-based training. The offline approach is implemented by allowing the user to use the walking support system from a start point to a goal point in a training environment and path following algorithm is employed. The user's intention represented by applied force/torque is logged during training. The logged data is segmented to correspond to a straight and curve segments in the training environment. The data is used to regenerate the path of the robotic walking support system. The error between the regenerated and the desired path is taken. In case large path error exists, an optimization program is employed to change the center of rotation until the sum of the square of the path error is minimized. A variable center of rotation controller as a function of applied torque is designed based on the new center of rotation. This is augmented and used in the actual control of the robotic walking support system. The new center of rotation controller based on offline approach is evaluated using S-path following and the mean of absolute of error is taken.

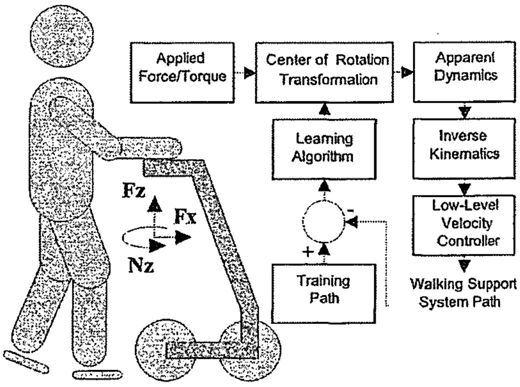

Fig. 2 Training block diagram

Chapter 6 discusses the high-level functions of the robotic walking support system "Walking Helper II". Aside from its motion control algorithm that adapts user's controlling characteristics, we also develop some high-level functions that are useful in the daily activities of a user. We consider a high-level function as a modular component of the overall control algorithm. Based on the state or situation of a user, a certain high-level function can be called to address the situation. High-level functions are important in enhancing the capability of the support system. First, we present the safety function of the support system, which is based on body force sensor. This is implemented by installing a force sensor between two plates. In normal obstacle collision, the reaction force of the hit object will cancel out the applied force of the user to the support system. This prevents the robotic walking support system from moving towards the obstacle. In addition, ambulatory function emulation is presented.

We also present a high-level function of the new robotic walking support system in assisting a user in a Sit-to-Stand movement. A Sit-to-Stand movement is a common activity of an elderly and we try to explore possible ways on how our new robotic walking support system can assist a Sit-to-Stand movement to a certain user. We present and analyze two approaches in implementing an assist to Sit-to-Stand movement. The first method we consider is a passive support. In this method, the support system is positioned in front of the user. The user then uses the support system's handle to execute a Sit-to-Stand movement. The second approach is active support and we try to support part of the knee torque. In this approach, a motion control algorithm is introduced such that the support system moves based on the desired support knee torque. The implementation and evaluation of the two methods are also discussed.

Chapter 7 discusses the summary of the study. It also discusses the future works and research direction of "Walking Helper II". As an example, research direction in estimating and predicting user's state (e.g. posture) based on relative position between the user and the support system, and user's intention in the form of applied force/torque. The estimation and prediction of user's state will improve human-robotic walker interaction.

論文審査結果の要旨

社会の高齢化を背景として、高齢者を対象とした歩行支援を実現する、知的歩行器に関する研究は数多く行われているが、従来から提案されているシステムは、非ホロノミックな拘束条件を持つ運動特性を有しており、高齢者や障害者の多岐にわたる障害に適応した、高い操作性を実現することは難しい。本論文では、歩行器の移動ベースに全方向移動機構を用いることによって、その運動特性を利用者に応じて変化させることにより、高い操作性を実現する、歩行器の新しい運動制御手法を提案するものであり、全編7章よりなる。

第1章は序論であり、本研究の背景と目的を述べている。

第2章では、全方向移動型歩行器とその基本的な運動制御システムを提案している。提案しているシステムは、人間の操作力に基づき直感的に操作が可能な歩行器を実現するために有用なシステムである。

第3章では、歩行器の操作力に対するみかけの回転中心（COR、Center Of Rotation）が制御可能な運動制御システムを提案するとともに、その操作性がCORの位置によって大きく変化することを示し、CORを可変にすることの有効性を実験により確認している。提案されたCORの位置に注目した歩行器の運動特性制御手法は、従来にない画期的な手法である。

第4章では、利用者の障害や癖等に応じて歩行器のCORの位置を制御し、その操作特性を利用者に適応させることによって、高い操作性を実現することが可能な新しい制御手法を提案している。提案する手法は、トレーニング環境を用いてシステムに利用者の特性を学習させ、実時間でCORの位置を制御し、操作性を改善する独創的かつ有用な手法である。

第5章では、一般的な環境で歩行器を利用する際に、その環境情報、運動情報、および歩行器に加えられる操作力情報を記録して、オフラインにて適切なCORの位置を決定する手法を提案している。この手法は、トレーニング環境等を用意することなく、日常の使用に基づいてCORの位置を更新していくことが可能となる実用的な手法である。

第6章では、開発した歩行器を用いることによって、歩行器の高機能化が実現できることを示している。具体的には、ボディーフォースセンサを用いた歩行器の安全性向上システムの提案や、杖や非ホロノミック拘束を有した車輪付歩行器などの歩行支援デバイスを模擬するための制御手法の提案、利用者の離床支援法の提案等を行っている。これらは歩行器の実用化に向けた必要不可欠な技術である。

第7章は結論である。

以上要するに本論文は、全方向移動機構を利用した歩行器を提案するとともに、その運動特性を利用者に応じて制御し操作性を向上することを目的とした新しい運動制御手法について論じたもので、機械工学、ロボット工学および福祉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。