Title	高齢者の歩容改善のための骨盤運動を考慮した歩行支援機の開発
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Citation	
Issue Date	2016-09
Type	Thesis or Dissertation
Text version	ETD
URL	http://hdl.handle.net/10119/13830
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学 位 の 種 類	博士(情報科学)
学 位 記 番 号	博情第 352 号
学位授与年月日	平成 28 年 9 月 23 日
論　文　題　目	高齢者の歩容改善のための骨盤運動を考慮した歩行支援機の開発
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論文の内容の要旨

The elderly population is growing fast all over the world. Japan is the most rapidly aging country, and its population aged 65 or above rose to more than 25 percent of the whole population in 2014. Japan is projected to become a super-aged society where those aged 65 or above account for about 36 percent by 2025. Population aging has caused significant challenges of caregiving. Recent advances in robotic technologies have allowed increasing attention to be paid to welfare or rehabilitation services in these rapidly aging societies. Such technological advances have made it possible to design and develop a wide variety of human-friendly assistive robotic systems. Among them, personal assistive mobility devices such as walker, cane, and wheelchair are strongly desired to keep the elderly independent.

A walker is a device for the elderly who need additional support to maintain balance and stability while walking. Basic traditional walkers mainly consist of a frame surrounded by four legs on the front and sides. And, body support is provided by the user holding onto the top of the sides. Robotic walkers with similar mechanical structures to the traditional walkers have emerged, but the installation of mechanical and/or electronic components is often required to promote safer ambulatory assistance. Recent technological advances have allowed the incorporation of a range of features into robotic walkers. Moreover, users utilize their own remaining ambulatory capability when walking with such devices, which plays an important role in helping users exercise. Therefore, the walker needs to be comfortable and easy to use.

Generally, elderly people tend to be in slow motion and suffer from delayed reaction time. Moreover, few are familiar with mechanical or electronic controls. When designing and developing robotic walkers for the elderly, an easy-to-learn and simple-to-use interface system capable of responding to complex and diverse environments is of particular importance. Similarly, the interface should be able to accommodate various individual levels of physical capability. Based on an interface which takes into consideration each of the above factors, the robotic walker prototype, the

JAIST Active Robotic Walker (JARoW), was developed.

The mechanical design of JARoW is compact, and its footprint circular, which reduces the potential for collisions with obstacles or walls. JARoW has three main structural parts: a base frame, an upper frame, and connecting rods. The base frame supports the superstructure, and is directly connected to the drive-train and equipped with two Hokuyo URG-04LX laser range finders (LRFs) as the interface system. The length of the connecting rod can be adjusted according to the height of users. Users are able to lean their upper body forward and place their forearms onto the upper frame.

As one type of personal assistive mobility devices, JARoW encourages elderly people to lead more active lives, with reduced need for assistance. Specifically, JARoW does not require specific manual controls or additional equipment. Toward the practical use of JARoW, a walking intent-based movement control was proposed, allowing it to accurately generate the direction and location of its movement in a way that corresponds to the user's walking behaviors.

In general, the gait parameters of individuals are not always steady during walking. Furthermore, JARoW should be able to accommodate various individual levels of physical capability. For the purpose, a challenge aims at analyzing the different gait parameters of users and applying the analysis into the JARoW's control. As one contribution, a two-layered Kalman filtering scheme and a particle filter-based tracking scheme was developed to estimate and predict the locations of the user's lower limbs, respectively. Based on these proposed schemes, the filtering function was implemented as a main function in the main controller. After the realization of the filtering function, JARoW could autonomously control its smooth motions adapting to the user's walking patterns. Furthermore, the success of the proposed controls for JARoW could be confirmed through extensive experiments where elderly subjects currently using traditional walkers participated.

Meanwhile, the human gait is generally nonlinear, and the center of gravity of the human body can be modeled as a motion represented in 3-D space during walking. The walking behaviors of elderly people with insufficient ambulatory capability can be distinct from several points. Since the elderly sway their body by the movements of upper and lower limbs, there include the following features: shorter stride lengths, longer step interval, and slower walking speed (strides per minute). Moreover, three features result in longer stance phase. The behavioral symptoms of their ambulatory capability are caused by physical deterioration at both cognitive and sensory levels, sequelae by injury, and an increased body sway due to a disability. From medical knowledge and these considerations, simulations and preliminary experiments were performed for changes in stride by the rotations of the pelvis. These results indicated that, by an appropriate force is applied to the pelvis, the force helps an elderly person increase their stride length.

With these results, a more innovative and practical design of the second generation assistive robotic walker (JARoW-II) was designed and fabricated. JARoW-II aims at helping elderly users in need of walking assistance maintain and enhance ambulatory capabilities healthily and independently. In addition to the basic functions of the previous prototype, JARoW-II has advanced features that facilitate pelvic rotation. The control concept of JARoW-II based on the interactive

control scheme of JARoW was designed, allowing the elderly to synchronize their walking patterns and the assisted pelvic rotation, resulting in walking assistance and rehabilitation.

Like JARoW, three omni-directional wheels enables JARoW-II under the maneuverability autonomously to move forward and backward, slide sideways, and rotate at the same spot. Such omni-directionality provides a very efficient means of direction control in highly cluttered environments, even in a narrow hallway or in an elevator. Toward easy yet reliable maneuverability, JARoW-II can be employed without the use of any additional equipment or manual controls. Moreover, a novel pelvis-driving unit was developed and integrated into JARoW-II, helping pelvis rotations by applying a desired force to the buttocks of the user in the roll and the yaw directions. The design of the JARoW-II and its control mechanism are explained in detail. Finally, the validity and effectiveness of the proposed control for JARoW-II are verified through extensive experiments in everyday environments, and the results analyzed and compared to previous findings. Specifically, to verify the feasibility of JARoW-II, five persons over the age of 70 participated in outdoor experiments. From these results, it can be confirmed that JARoW-II could provide its potential users with easy, reliable assistance and enhance ambulatory capabilities.

Keyword: robotic walker, human-robot interaction, Easy maneuverability, walking intent, welfare robotics, reflecting pelvic movements

論文審査の結果の要旨

加齢や疾病などによる歩行能力の衰えた人を支援するための新しい概念の歩行支援ロボットシステム JARoW I と JARoW II の 2 種類を開発し、それぞれの有効性を動力学シミュレーションおよび実機実験により検証した論文である。先ずは、アクティブ型歩行支援機として操縦装置を必要としない JARoW の制御システムの頑強性を高めることを目指し、足の位置の検出精度並びに路面の凹凸や斜面、使用者の体重などの外乱の影響を考慮に入れた制御アルゴリズムを実装した。さらに、粒子フィルターを用いて歩行者の足の位置と歩行速度を予測することにより、使用者の足の動きと同期する JARoW の自然な動きを実現した。JARoW の定量的な評価のため、人の足先位置の知覚誤差を考慮した追従率を定義し、屋内外の様々な路面環境下における有志の高齢者による歩行実験で制御システムの有効性を確認した。機械・電子的なデバイスによるインタフェースに疎い高齢者の使用を想定し、人とロボットとのインタラクションの観点からも違和感なく誰でも操縦できる利便性を重視したシステムとして高く評価できる。

歩行支援機を介護予防やリハビリテーションへ応用することを目指し、若年者とは異なる高齢者の歩行の特徴を多方面の視点から分析した。一般に歩行率に依存する老人型歩行から脱皮させるために、若年者の理想的な骨盤の旋回運動を再現した座部機構およびその 3 次元駆動システムを開発した。若年者の歩行周期における骨盤の 3 次元運動パターンの数学的なモデリングを行い、使用者の歩容に合わせた制御パラメータを導出することによって、足の予測位置に同期する

JARoW の動きのみならず、座部機構の動きまでを連動制御するシステムを構築した。高齢者の骨盤の旋回を促すことで、スライド長の増加およびばらつきの減少、歩隔の減少、両脚支持期の減少などの高齢者の歩容の改善が見られ、長期間の使用によって若年者型歩行を意識させることにつながると期待される。歩行者の前頭面から見たときの左右の重心の動揺を抑えることは、これまでになかった独創的な機構となっているので、歩行支援ロボット分野において新しい方向性を提示したものである。

以上、本論文は、老人型歩容の改善について適切な骨盤運動による重心動揺を抑える独創的なシステムを提案したものであり、学術的に貢献するところが大きい。よって博士（情報科学）の学位論文として十分価値あるものと認めた。