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論文の内容の要旨

In the last decade, several robotic wheelchairs possessing user-friendly interfaces and/or autonomous functions for reaching goals have been proposed to meet the needs of an aging society. The elderly and disabled currently use different kinds of wheelchairs that are either manually controlled or powered by a control system. Although wheelchairs make it possible, for their users to go out alone, users are in practice, often accompanied by companions such as friends, families, and caregivers. The workload of assistive companions can be reduced with the help of motorized wheelchairs. However, even motorized wheelchairs have some shortcomings and are discouraged by some doctors, especially in cases where the elderly need to navigate urban environments and perform tasks such as boarding buses or climbing up a certain height. Thus, in designing new wheelchair technologies, it is important to consider how we can reduce the caregiver's workload while overcoming the existing shortcomings of wheelchairs. Autonomous wheelchairs are a potential solution to these issues, which could also have the option of granting many elderly wheelchair users the ability to control their wheelchairs on their own. In fact, this dissertation reviewed that around 3 million people could benefit from such wheelchairs. However the large majority of research to date has focused on indoor navigation. Thus, this dissertation is specifically concerned with navigation in outdoor urban environments while considering practical issues such as the cost of sensors and the computational cost of the robotic wheelchair. More specifically, this dissertation is aimed at first developing and designing a sensing system which can detect conditions in outdoor terrain for the wheelchair to run smoothly. The dissertation then focuses on getting precise measurements using a bidirectional sensing system with a single 2D laser for boarding and disembarking buses autonomously in urban environments. The empirical part of this dissertation was conducted throughout the study period and involved developing an autonomous bus boarding wheelchair system that moves independently with a companion or caregiver in urban terrain to reach bus stations and the wheelchair also has the capability to find bus doors using precise measurements and then boards using mechanically adjusted wheels.

To achieve these goals, the dissertation first proposes a robotic wheelchair system that is able to classify the type of outdoor terrain according to their roughness for the comfort of the user and also control the wheelchair movements to avoid step edges and watery areas on the road. This dissertation found that the wheelchair's terrain surfaces can be classified into four different categories. These are rough surfaces, watery places on the road, indoor plain surfaces, and dirt tracks. These roads may have different conditions, which can be dangerous for the wheelchair user due to the risk of sudden accidents when driving over them. Suppose a wheelchair follows the caregiver but s/he misses hazards such as bumpy/pit areas or watery spots. If the wheelchair were to not actively look for such hazards, it could fall and lead to injury of the occupant. Moreover, the wheelchair's speed for different surface areas should not be same. The wheelchair's speed needs to be automatically controlled with care. For this reason, detecting the type of surface is a necessity. An artificial neural network based classifier was constructed to classify the patterns and features extracted from the Laser Range Sensor (LRS) intensity and distance data. The overall classification accuracy was found to be 97.24% using extracted features from the intensity and distance data. These classification results can in turn be used to control the motor of the smart wheelchair. Moreover, the computed 3D surface elevation map could be used for deciding whether to move-on, slow down the speed, or to avoid watery and muddy areas on the road. Finally, this classification method was implemented on the wheelchair to validate its effectiveness by an experiment in which the proposed wheelchair system could detect watery places on the road and avoid them in a very efficient manner.

Classification of terrain is not all about smooth navigation where smart wheelchair systems aim to reduce the workload of the caregiver. In this dissertation, a novel 3D sensing system was introduced. It consists of a triangular shaped apparatus with undistorted reflecting mirrors for vertical and horizontal sensing of the floor with a conventional single 2D Laser range sensor and we name it the Bidirectional Sensing System (BSS). Conventionally, 2D laser sensors have a wide-angle horizontal field of view. We used a 2D LRF (HOKUYO) that has a horizontal angle view field of 270°, with a measuring interval angle of 0.25°. Typically, researchers use two or more such laser sensors to obtain vertical and horizontal sensing points for the measurement of heights. However, a single scan from the LRF captures 1080 values in 25 ms, representing a viewing angle of 270° but we do not need to scan all 270° in the horizontal field of view. On the other hand, we do need some vertical scan data to detect steps. Thus, we divided the total view angle into three parts with a 90° view angle each by using three undistorted reflecting mirrors. All acquired data from the 2D laser had outliers removed so that we could accurately measure the step size of stairs or the elevation gaps of bus doors. In order to remove any undesirable artifacts, we used the median values and standard deviation of the data series. Deploying our BSS tilted towards the ground at 45° and 100 cm above the ground, the slope was calculated from the laser data to find whether it was positive or negative. A positive tangent indicates a planar surface and a negative slope indicates steps. In our system, the scanning points are separated in such way that they give two horizontal scanning lines and one vertical scanning line. For the vertical positional data, we get distributions for every step of a given height like in the case of stairs or the doorstep of a bus in the *y–direction* and the *z–dtrection*. Here, *y* and *z* indicate the horizontal and vertical spaces of the data plot respectively. The *z–values* give the height whereas the *y–values* give the width, respectively. The standard deviation and mean of each direction are used for finding outliers. Then the mode of the distribution of the values are applied to find the peak points and lowest point. The Euclidian distance of those, two points are then used to determine the height of the steps. For finding the mode, we used 1 cm intervals in each direction. Therefore, this sensing system is able to calculate precise measurements of bus doorsteps or staircase steps for climbing. For measuring the accuracy of this sensing system, we calculated stair and bus doorstep heights in practical scenarios and were able to measure heights with an error of ± 1cm.

Finally, the major objective of this dissertation was to build an autonomous wheelchair to board buses. For bus boarding, we need two vertical scanning lines set apart at a distance the same as the wheelchair width so that it can avoid collisions with the bus door. Therefore, we used two BSSs and a calibrated camera equipped along the same axis on a 78 cm long bar edge tilted towards the ground. This gives two vertical sensing lines from the far left and right of the sensors and four horizontal sensing lines across the vertical lines. We merge the horizontal data from the top and bottom so that we can receive a single distance value from both sensors. Additionally, we mapped these 3D point cloud data onto an image for verification and experimentation.

The vertical sensing positions of the sensors start from 3 cm by the front wheels to check for obstacles. Our sensing area also covers 1 meter of the distance ahead of the wheelchair. The front area of the sensing lines are important to find other obstacles like other passengers, bus seats, or luggage. Once the wheelchair has been instructed to board the bus, our system can sense if this area is free to board, otherwise it sets itself back. This feature adds an extra layer of safety for our wheelchair. Also, before receiving any bus boarding commands, our wheelchair is able to detect the bus door using an image recognition system. For that, the YOLO Darknet based object detection approach is employed. For approximate detection of buses and bus doors with doorsteps, we trained our image recognition system with 400 different images of buses, bus doors and doorsteps for each class. In addition, the overall precision of the system was measured using the Intersection of Union (IoU) method and we achieved an overall 88% average. In real experiments with a buses, we see the effectiveness in detecting the buses and bus doors. Our wheelchair also approached a real bus and measured the doorstep height to be 14.9 cm where the actual height was measured to be 15 cm.

In addition, we made our wheelchair capable of autonomously following its companion on way to the bus station for smooth running on terrain and then had it wait for the bus. In our setup, once our image recognition system detects the bus, it changes its position to move to the approximate location of the door. Once the door is detected, the wheelchair is guided by the BSS module to find the bus doorsteps and calculates the height and width of the door for boarding. To achieve these tasks, our wheelchair operates in three modes (1) Companion Following Mode, (2) Autonomous Mode for boarding and (3) Manual Mode. The companion following mode is in operation while the wheelchair is going to the bus stop and after getting off from the bus. The autonomous mode is operated while the wheelchair is either boarding or getting off the bus. As space is limited inside the bus, the wheelchair is operated in manual mode with a joystick by the companion for adjusting the wheelchair position towards the bus door for safe navigation. We conducted several indoor mock-up bus experiments and real bus experiments for bus boarding with a newly trained image recognition server that can detect buses and bus doors as well as doorsteps. Based on the experimental results of this research, it can be concluded that a new mechanism of bidirectional sensing using a single 2D laser for getting the heights of bus doorsteps for autonomous bus boarding was successful. Moreover, we demonstrated successfully operation of the proposed robotic wheelchair system using our method, which grants freedom of movement to the wheelchair user in urban environments.

論文の審査結果の要旨

当論文審査委員会は、当該論文の発表会を平成 30 年 7 月 31 日に公開で開催し、詳細な質問を行い論文内容の審査を行った。その論文発表を含む学位論文の審査の結果、本提出論文を博士（学術）の学位論文として合格と判定した。以下に審査結果の要約を示す。

本提出論文は、自律的に都市環境内を走行できるロボット車いすに関して検討したものである。高齢化社会の進行に伴い、車いすのニーズが高まっている。そこで、高齢者でも容易に使えるように自動走行などの支援機能を有するロボット車いすの研究開発が盛んになっている。しかし、これまでのロボット車いすでは、室内や整備された屋外環境での走行が中心であった。高齢者の行動範囲を広げるためには、さらに多様な環境で走行できるロボット車いすの実現が望まれる。本論文は、このようなロボット車いすの実現に向かって、都市環境で遭遇する可能性のある様々な状況に対応する方法について検討したものである。具体的には、屋外を走行する場合に路面の状態を認識し、水たまりがあればそれを避け、路面の状態が平坦でない場合は速度を落として走行することのできる車いすを検討した。また、都市環境で移動する場合にはバスを用いることも多いが、バスに自動で乗降できる機能についてセンサシステムを検討し、共同研究先で開発された段差に対応できる車いすのハードウェア上に実装し、実際にバスの乗降が可能なことを示した。

本論文は 6 章からなる。まず、第 1 章では、上で述べたような本研究の背景、研究目的について述べている。そして、これまでのロボット車いすの研究についてまとめ、さらに環境認識に用いられるセンサや段差を走行できる機構をもつ車いすについて調査している。

第 2 章では、路面の状態の認識について検討している。ロボット車いすでは、レーザを照射し、その帰還までの時間 (time-of-flight) により物体までの距離を計測するレーザ測域センサが障害物の検出・回避のためによく用いられる。本論文では、そのセンサにより得られる路面までの距離情報とセンサに戻って来るレーザ光の強度情報を用い、すなわち、路面の荒さと光の反射特性に関連する情報を用い、路面を舗装道路、不整地、屋内、水たまりの 4 つに識別する方法を提案している。これを実際の車椅子に実装し、実験により車いすが水たまりを避けながら移動できることを示した。また、不整地などで路面が荒い場合には、速度を自動的に落として走行する車いすを実現した。

第 3 章では、バスの自動乗降のためにレーザ測域センサと鏡を組合せたセンシングシステムを提案している。通常のレーザ測域センサでは、一つの平面上について、周囲の物体までの距離という 3 次元情報が得られる。路面上にある障害物を検出するには、一つのセンサで車いすの前方の平面上を調べるだけでよいが、バスに乗降するためには、バスのドアの左右端の位置に加えて、ドアの床部分の高さの情報が必要になる。センサ前方のすべての空間に対して 3 次元情報を得られるセンサもあるが、非常に高価である。水平方向と垂直方向の計測のために水平方向と垂直方向に複数のセンサを設置したり、モータによる機構を用いて、一つのセンサを回転させる方法も提案されている。しかし、複数のセンサを用いれば高価になり、モータ用いれば動作に時間がかかるという問題が生じる。そこで、一つのレーザ測域センサを 3 枚の鏡で囲むことにより、水平面と垂直面の 3 次元情報を取得できるセンサシステムを開発した。このシステムでは、さらにビデオカメラを組合せて、どの部分についての 3 次元情報を得ているかが容易に分かるようになっている。実験により、このセンサにより階段の高さが正確に計測できることを確認した。また、バスのドアの高さの計測も可能なことが示された。

第 5 章では、開発したロボット車いすが実際のバスに乗降できることを実験により示している。開発した

センサシステムを共同研究を行っているトヨタ自動車と東京大学で開発中の６輪で段差に対応できる車椅子に取り付け、そのセンサ情報を用いて車いすの移動を制御できるようにした。所属研究室でこれまでに開発した同伴者に付いて自動走行するロボット車いすの技術と組合せ、バスの近くまでは同伴者に付いて行き、そこからは自動でバスのドアに正対するように位置を制御し、それからバスのドアの高さを計測しながら、各車輪の高さを制御してバスに乗車する。降車の場合も、バスのドアの端と道路面を検出し、車輪の高さを制御して降車する。バスのドアの実物大模型を作り、それを用いて動作を確認した後、実際のバスを用いて乗降の実験を行い、提案のロボット車いすでバスに自動乗降が可能なことを実証した。
　最後に第６章で、全体を総括し、今後に残された課題を議論している。

　今回の研究では、ロボット車いすが都市環境を走行するために必要な路面状況の認識とバスの乗降について検討した。路面状況を認識して水たまりを避けることなどは、屋外を走行するロボット車いすの実現には重要な技術である。バスの乗降については、実用化のためにはより確実、迅速に動作する車いすの機構の開発が必要だが、自動的にバスに乗降できることを示したことにより、高齢化社会でニーズの高まるロボット車いすの実現に必要な基盤技術を開発したものと評価できる。
　以上のように、本論文の内容は、学術的に意義のある研究であると判断できる。よって、当学位論文審査委員会は、本論文を博士（学術）の学位論文として合格と判定した。