Ego-trajectory Estimation of Electric Wheelchair Using Millimeter-Wave Radar

Ryuei Maruyama[1], Ryuto Terawake[1], Keiji Jimi[2] and Kenshi Saho[1,*]

[1]*College of Science and Engineering, Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu-shi, Shiga 525-8577, Japan*
[2]*Graduate School of Science and Technology, Gunma University, 29-1 Honcho, Ota-shi, Gunma 373-0057, Japan*

Abstract

This paper presents fundamental experiments on self-localization and ego-trajectory estimation of an electric wheelchair using a millimeter-wave multi-input multi-output (MIMO) radar in environments containing multiple static objects. Accurate estimation of the wheelchair trajectory is achieved by combining a frequency-modulated continuous-wave (FMCW) radar positioning with an iterative closest point (ICP) matching algorithm that is adapted to the radar data points, and the feasibility of the proposed method is demonstrated with real data. Since the operation of electric wheelchairs can be challenging for elderly users, this research aims to contribute to the application of autonomous driving technologies for mobility support. These results indicate the potential contribution of millimeter-wave radar to autonomous mobility support systems for elderly people.

Keywords

Millimeter-wave radar, MIMO FMCW radar, Autonomous wheelchair, ICP matching

1. Introduction

Autonomous driving technology is expected to improve the convenience of society. This technology is considered important in the field of autonomous driving for automobiles and is the subject of extensive research and development. Alternatively, another important application is autonomous driving for wheelchairs. For electric wheelchairs primarily used indoors, it is difficult to utilize the global navigation satellite system, which is commonly used in autonomous driving systems [1]. Therefore, self-localization and ego-trajectory estimation using sensors installed on the wheelchair are necessary. For this purpose, camera and LiDAR technologies, which have been primarily studied in the robotics field, are being considered, and their effectiveness is known [2, 3]. However, cameras raise privacy concerns for wheelchair users. LiDAR fails in smoke or cluttered environments. For this reason, it is necessary to have other sensors available in case LiDAR cannot be used.

As another candidate sensor for wheelchair ego-trajectory estimation, millimeter-wave Multi-Input Multi-Output (MIMO) radar has attracted attention because it can measure range (distance) and angle as well as the velocity information, and can operate stably even in the presence of

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*Corresponding Author
saho@fc.ritsumei.ac.jp (K. Saho)
0000-0003-2088-1231 (K. Saho)

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various obstacles [4]. However, its relatively low spatial resolution hampers precise recognition of the surrounding environment that is essential for the self-localization and ego-trajectory estimation. Sensor fusion systems with camera, LiDAR, and radar have been proposed for autonomous driving applications [5, 6]. However, they incur high costs and data-collection difficulties and are not necessarily suitable for low-cost, privacy-preserving small mobile platforms. Thus, although ego-trajectory estimation using only the MIMO radar is a challenging task, it should be considered as a candidate sensing system for the electric wheelchair.

This study presents an accurate estimation of the ego-trajectory of an electric wheelchair using only millimeter-wave MIMO radar. Our proposed method estimates the variation of the relative positions of surrounding static objects to estimate ego-trajectory using the range-angle information obtained from the radar as a landmark map. The feature of the presented method is that environmental features for the self-localization are extracted from only the radar information, and the measured features themselves are used as a landmark map for the matching process of the estimated positions of each static target between the measurement time steps. This study adapted the iterative closest point (ICP) algorithm, which is known as the general matching method for the LiDAR data [7], to the measurements obtained from MIMO installed on the wheelchair. The experimental results showed the feasibility of accurate ego-trajectory estimation via the MIMO radar-based self-localization using the proposed method. The experiments reported in this paper serve as preliminary baseline studies to demonstrate the applicability of the proposed MIMO-radar–based ego-trajectory estimation method.

2. Ego-trajectory estimation method

The objective of this research is to verify whether ego-trajectory estimation using millimeter-wave radar can be applied to a moving platform such as an electric wheelchair. Previous studies have mainly focused on localization based on static objects, and the effectiveness of this process for moving vehicles has not been sufficiently investigated. To address this challenge, we apply the following radar-based measurement and ICP matching method.

The ranges (distances) and angles of the detected objects are estimated via the processing of the received IQ signals. Figure 2 outlines a processing procedure of the received signals in the proposed method. For the FMCW radar, a Fourier transform is applied to the received signals to measure range R of the detected targets [9], and azimuth angle θ relative to the heading direction of the wheelchair was estimated using a beamformer method [10]. For each time step k, corresponding to one FMCW transmission, we generate the range-angle spectrum $P_k(R, \theta)$. Then, significant peaks in $P_k(R, \theta)$ are extracted as the measured positions of multiple static targets. For each detected target at time step k, the position in the xy-plane is $(x_k, y_k) = (R_k \sin\theta_k, R_k \cos\theta_k)$.

Next, the detected positions in the distance-angle spectrum obtained were input to a multi-target tracking filter [11] to remove peak points corresponding to ghost images caused by multipath and to remove the random noises in the estimated positions. A Kalman filter using a constant velocity model in the xy-coordinate system was used for the tracking filter. In the Kalman filtering, the state vector is $(x_k\ y_k\ v_{xk}\ v_{yk})$ where v_{xk} and v_{yk} are the velocities for each axis, and the association of multiple targets used a nearest-neighbor method [11]. The tracked points corresponding to all detected targets at time step k are defined as x_k.

Finally, the displacement of the points of detected targets between successive frames is computed with the ICP algorithm [7]. Because surrounding objects are assumed to be static, this displacement equals the ego-vehicle displacement, and cumulative integration yields the ego-trajectory. In other words, the positions of stationary objects in the vicinity are measured, and the movement of the vehicle itself is estimated from these amounts of movement, thereby estimating the movement path of the vehicle. The procedure of the ICP algorithm for the radar data points x_k is as follows. The objective of the ICP matching is to estimate the orthonormal matrix R and translation vector t that align the data points x_k and x_{k+1} (the data points at the next time step), which is expressed as $x_{k+1} = Rx_k + t$. The algorithm to determine R and t are as follows:

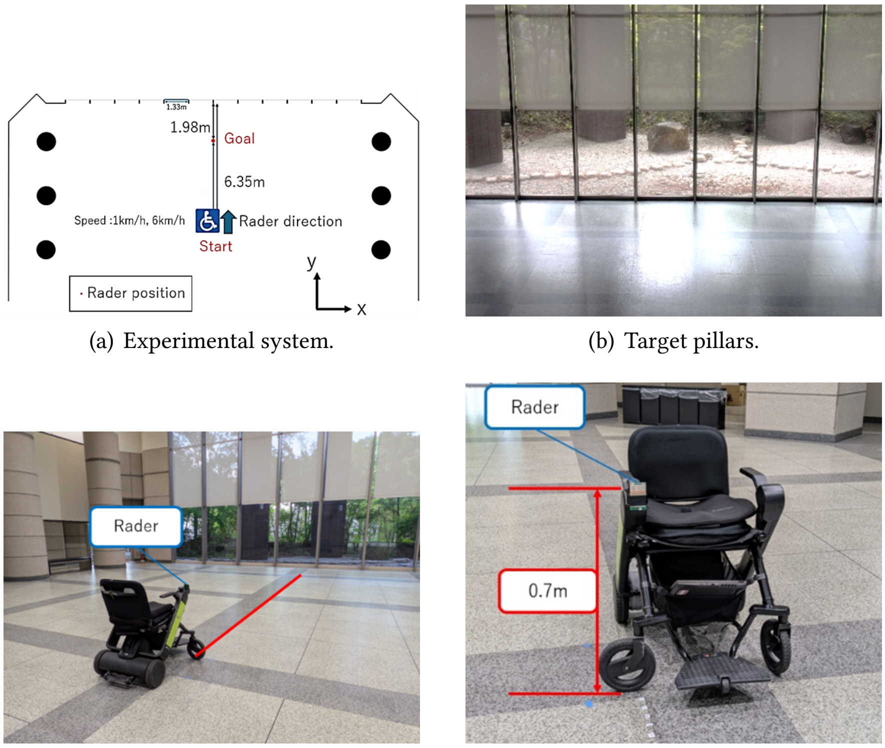
1. For each point in x_{k+1}, find its nearest neighbor in the points x_k and pair them.
2. Let c_k and c_{k+1} be the centroids of x_{k+1} and x_k, respectively. Translate both sets so their centroids coincide with the origin.
3. Compute the correlation matrix H with $(x_k - c_k)(x_{k+1} - c_{k+1})^T$.
4. Perform singular value decomposition to obtain $H = U\Sigma V^T$, where U and V are orthogonal matrices and Σ is diagonal.
5. Compute the optimal rotation with $R = VU^T$ and the optimal t with $t = c_{k+1} - Rc_k$.
6. Move x_k by applying R and t. Repeat steps 1–5 until convergence or a preset number of iterations is reached. To accumulate the overall transform, update the total rotation R_{total} and total translation t_{total} each loop: $R_{\text{total}} \leftarrow RR_{\text{total}}$ and $t_{\text{total}} \leftarrow Rt_{\text{total}} + t$.
7. Using obtained R_{total} and t_{total}, the ego-trajectory is estimated as $x_{k+1} = R_{\text{total}}x_k + t_{\text{total}}$.

3. Experimental setup

Figure 1 shows the experimental setup. The MIMO radar was mounted on an electric wheelchair. The positions of surrounding static objects are measured from the moving wheelchair, and ego-trajectory of the wheelchair is estimated via relative movements of the detected objects. The proposed method estimates the ego-vehicle trajectory from the received signals of a millimeter-wave MIMO radar mounted on an electric wheelchair at a height of 70 cm. The wheelchair was assumed to travel at speeds of 1 km/h and 6 km/h along a straight line. In the situation of Figure 1, the objects detected by the radar are the pillars in front of the wheelchair. Table 1 shows the specifications of the radar. The radar is 79-GHz FMCW (frequency-modulated continuous-wave) radar that is commercially used for automotive radar. The radar receives IQ (in-phase/quadrature-phase) signals reflected from the surrounding objects via a synchronous detection using transmitted signals.

4. Results and discussion

This subsection presents the results for the electric wheelchair moving at a relatively low velocity of 1 km/h. Figure 3 shows an example of the range-angle spectrum $P_{85}(R, \theta)$ and we confirmed that some target pillars were detected. Note that all pillars in the measurement



(a) Experimental system.

(b) Target pillars.

(c) True trajectory of the wheelchair.

(d) Radar-mounted electric wheelchair.

Figure 1: Experimental setup.

Table 1

Radar specifications.

Item	Values
Radar module	S-TAKAYA T14RE_01080108_2D 79 GHz millimeter-wave radar module [8]
Transmission signal	FMCW signal comprising only up-chirps
Sweep frequency range	77.4–80.8 GHz (Bandwidth: 3.4 GHz)
Antenna configuration	3 TX, 4 RX, Antenna separation: 1.9 mm
Chirp period	112 μs
Frame rate (Measurement frequency)	10 Hz

area were detected in some time steps. Figures 4 and 5 show the estimated ego-trajectory and absolute estimation error for each time step, respectively. Accurate trajectory estimation with a mean error of 0.0136 m was achieved. This result indicates that the proposed method achieves accurate self-localization and ego-trajectory estimation based on the robust detection of multiple static objects using only the millimeter-wave radar and the ICP matching algorithm that is generally used in the LiDAR sensing.

Then, we investigated the wheelchair moving at a larger velocity of 6 km/h. Figure 6 shows an example of the range-angle spectrum $P_{42}(R, \theta)$. Similar to the case for 1 km/h, we can

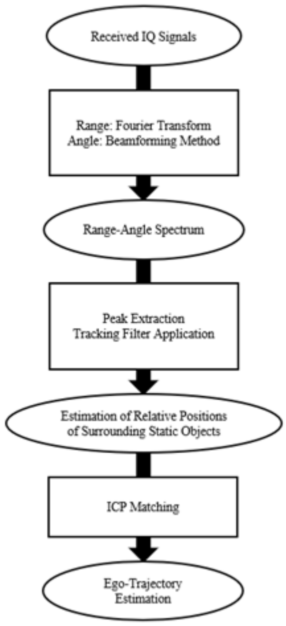


Figure 2: Procedure of the ego-trajectory estimation method.

confirm that most target pillars are detected. However, some ghost images are also confirmed. This is because the effects of the multipath in each frame are large and the received signal power from the pillars become small due to the relatively high speed of the wheelchair. Figures 7 and 8 show the estimated ego-trajectory and absolute estimation error for each time step, respectively. Because of the pillar position errors in Figure 7, the ego-trajectory contains larger errors compared with the case of 1 km/h. When the electric wheelchair moved with relatively fast speed, unexpected leftward errors were observed. Although the effects of the ghost images were canceled by the tracking filter to some extent, they were not completely removed. However, as indicated in Figure 8, the maximum estimation error was approximately 5 cm at the end of the observation. Thus, the proposed method achieved accurate radar-based ego-trajectory estimation of the wheelchair. In the proposed method, the accumulation of errors caused by false images can lead to errors increasing over time. To address this issue, it will be necessary in future research to apply other robust matching algorithms for multi-target tracking and orbit estimation such as multi-hypothesis tracking [11].

Figures 4 and 5 are plotted with points; however, due to the large number of acquired frames, the points are densely distributed and appear as continuous lines.

5. Conclusion

This study proposes an ego-trajectory estimation method using only a millimeter-wave MIMO radar and demonstrates its effectiveness with real wheelchair data. We adapted the self-

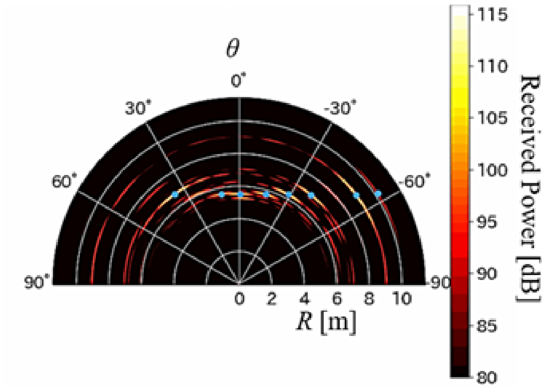


Figure 3: Example of range-angle spectrum for the velocity of 1 km/h. Blue points denote the detected pillar targets.

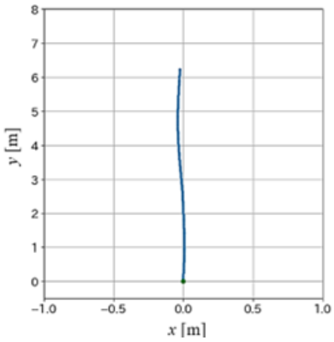


Figure 4: Estimated ego-trajectory of the wheelchair for the velocity of 1 km/h.

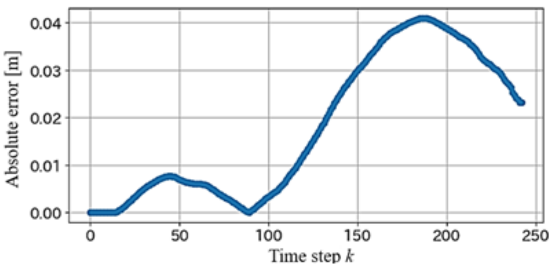


Figure 5: Absolute error of the trajectory at each time step for the velocity of 1 km/h.

localization and ICP matching algorithms for the MIMO radar mounted to the wheelchair ego localization. The experimental results demonstrated the accurate ego-trajectory estimation with an error on the order of 1 cm. However, relatively larger errors were observed at the higher speed, and our future study will focus on improving performance in such cases by using other methods that can achieve high-resolution measurements such as adaptive antenna techniques. Furthermore, further performance examinations in other environments with more complicated

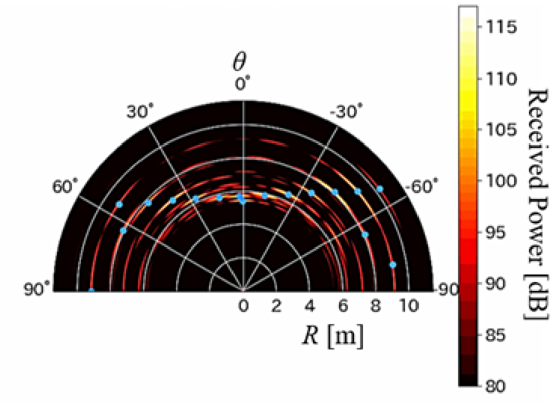


Figure 6: Example of range-angle spectrum for the velocity of 6 km/h. Blue points denote the detected pillar targets.

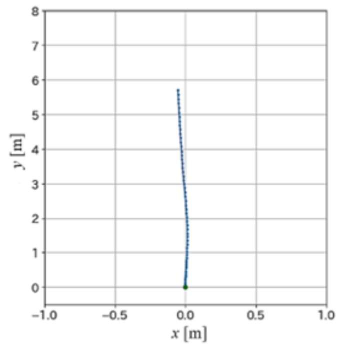


Figure 7: Estimated ego-trajectory of the wheelchair for the velocity of 6 km/h.

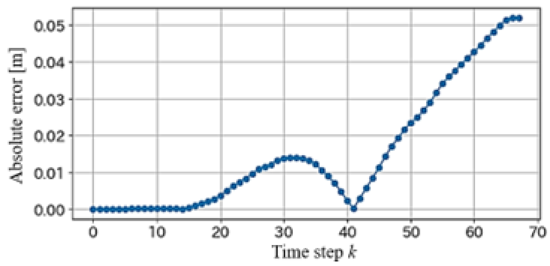


Figure 8: Absolute error of the trajectory at each time step for the velocity of 6 km/h.

static targets and arbitrary orbits of wheelchairs are important.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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