Tracking of wheelchair users in dense crowds

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Abstract— This paper proposes a tracking algorithm for wheelchair users fusing Inertial Measurement Unit (IMU) data and trajectory information of surrounding people. This approach is based on a hybrid tracking system for laboratory experiments with pedestrians in dense crowds consisting of cameras and IMUs. A camera system on the ceiling forms the basic detection and tracking system. Current experiments with heterogeneous crowds have arisen new requirements to this system. Participating wheelchair users tend to get occluded by surrounding people which leads to incomplete trajectories. To fill those temporary gaps the data of IMUs that are attached to the wheelchairs are used. The IMU trajectories are calculated with an Inertial Navigation System (INS) algorithm. The orientation is calculated with a sensor fusion filter and the distance is estimated by numerical integration of the acceleration measurements. To limit the drift the calculated velocity of the wheelchair is restricted to the velocity of the pushing person. Preliminary studies were performed to investigate this approach and resulting trajectories are presented.

Keywords—indoor localization; wheelchair tracking; hybrid tracking; Inertial Measurement Unit (IMU); Attitude and Heading Reference System (AHRS); camera-based tracking system; Inertial Navigation System (INS); crowd; data fusion

I. INTRODUCTION

Although pedestrian streams are a part of everyday life, their basic nature and characteristics cannot be described in detail yet. However, the understanding of the behavior of pedestrians in front of bottlenecks, the movement of crowds in restricted areas or the turning and merging of pedestrian streams is important for safe designs of buildings or event areas. There are even discrepancies in basic knowledge such as the fundamental diagram which describes the relation between density, velocity and flow. Among varies studies this diagram shows significant differences [1]. For a comprehensive analysis of pedestrian dynamics, a reliable database of precise and diverse trajectories is needed. To fill this database several laboratory experiments with a large number of people have been conducted detecting their trajectories. Such experiments provide the possibility of specifically controlling and studying factors which influence the dynamics of a crowd.

Within the projects Hermes [2] and BaSiGo [3], which were funded by the Federal Ministry of Education and Research (BMBF) of Germany, large scale pedestrian experiments were performed. The movement of hundreds of people was observed in distinct geometries, varying parameters such as the width of a corridor or bottleneck, the motivation of the persons or the density of the crowd. The resulting trajectories are, amongst others, used for simulating evacuation scenarios and help to recognize critical situations. Even if various parameters were investigated in these projects the impact of a heterogeneous composition of a crowd on its dynamics needs further examination. Within the scope of the latest BMBF project SiME [4] one factor of heterogeneity is currently under investigation. The associated experiments involved pedestrians with and without disabilities to understand the influence of this diversity on the evacuation process. As said in [5] there is a need of empirical data regarding evacuation processes in various built environments with disabled people. With the findings of the SiME experiments present evacuation models will be evaluated and improved.

To obtain new insights, e.g., for modeling pedestrian dynamics, the trajectories of participants of an experiment must be detected and analyzed first. The detection is realized by a camera system consisting of several cameras attached to the ceiling to cover the desired area. A critical issue of the camera detection system is the occlusion of pedestrians caused by the perspective view and different heights of the participants. For the SiME experiments special attention was paid to people using a wheelchair. To ensure the gapless detection of their trajectories the wheelchairs were equipped with two Inertial Measurement Units (IMUs) and one additional sensor on the head of the wheelchair user. The data of the IMUs are used to calculate the trajectory when the wheelchair user is not visible to the camera system.

The focus of this paper is the evaluation and fusion of IMU and camera data of a preliminary study which was conducted before the SiME experiments to evaluate the hybrid tracking approach. A real-time processing of the IMU data is not necessary because the trajectories are not needed during the experiments and are determined afterwards which also applies to the camera data.

II. PRELIMNARY STUDIES

In first studies the tracking of an evacuation chair which represented the movement of an actual wheelchair was investigated. The evacuation chair was pushed by one person walking an oval-shaped path for two times within an area of approximately 4×6 meters. Walking along this path took the test persons 43 seconds. The run was recorded by a camera on the ceiling. For an easier detection markers in form of colored caps on the heads are used (see Fig. 1). The camera was aligned in the center of the oval. In this way, there was no occlusion and gapless trajectories were extracted with the software application

PeTrack [6]. Those trajectories are detected with centimeter-level accuracy and are considered as the ground truth. Thus, the camera-based trajectory of the person in the evacuation chair can be used for the validation of the calculated corresponding IMU trajectory.

The evacuation chair was equipped with four IMUs (SABELSense, Nathan, Australia [7]) as shown in Fig. 2. The 9DOF IMUs consist of an accelerometer, a gyroscope and a magnetometer with 3DOF respectively. Since the camera system tracks the movement of the participants head one additional IMU was placed under the cap of the wheelchair user. For data fusion purposes, vertical and horizontal distances between the sensors were measured. The IMUs were synchronized via a wireless network at the beginning and end of the experiments.

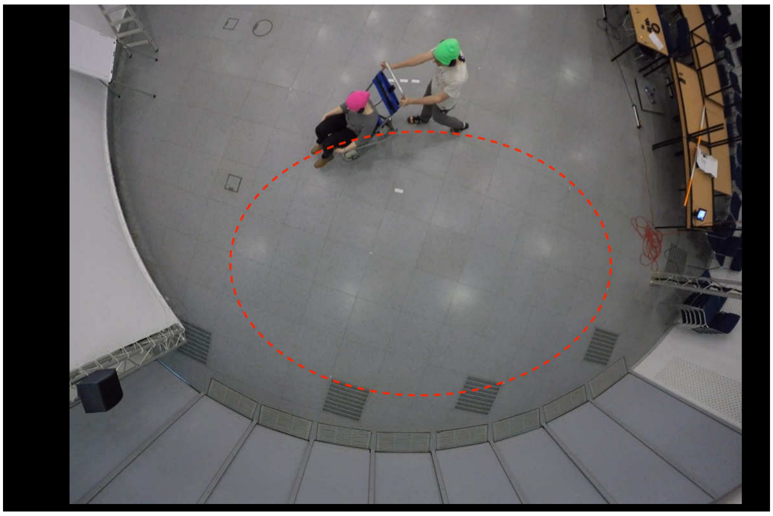

Fig. 1. View of the camera with the rough path marked with a dashed red line.

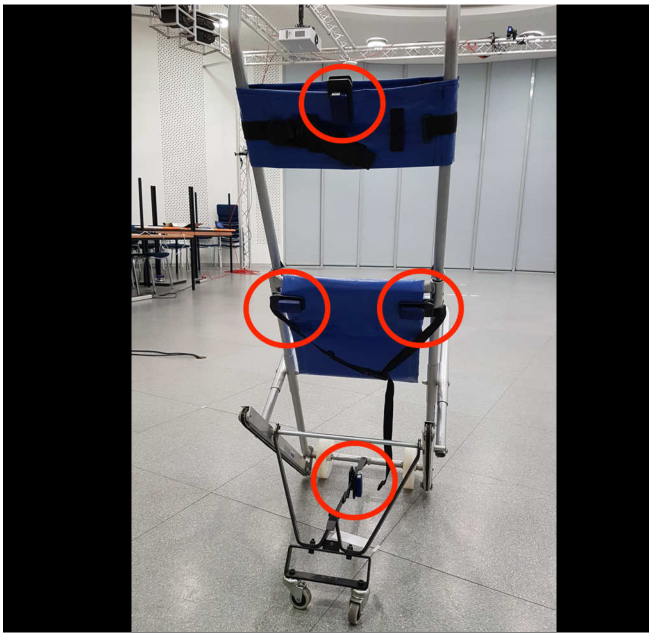

Fig. 2. Evacuation chair equipped with four IMUs marked with red circles.

III. Tracking Algorithm

To track the movement of the wheelchair with the IMU measurements the orientation and covered distance of the sensor needs to be calculated. As a first step the data of the sensor placed at the upper backrest are used only. Due to the high drift the velocity of the pushing person is used to constrain the velocity of the wheelchair user.

A. Related work

Due to the homogenous movement of the wheelchair the localization of robots as in [8,9] is a related area of research. Both approaches fuse IMU and odometry sensor data to improve the tracking. For this purpose, specific odometry sensors would be needed.

In [10] two IMUs (also SABELSense) were attached to each wheel on opposing spokes for distance estimation by calculating the rotation of the wheel with a given radius. For heading estimation one additional IMU was placed centrally under the wheelchair. This approach requires the knowledge of the accurate wheel radius measurement which is not applicable with a high diversity of wheelchairs attending the SiME experiments. In addition, the condition of opposing spokes is not fulfilled for each wheelchair. Therefore, another tracking approach is investigated by attaching several sensors to the rigid part of the wheelchair. Knowing the fixed relation between the sensors the signals of the different IMUs shall be fused to obtain a better trajectory.

B. IMU tracking

For calculating the trajectory the basic approach of an strapdown inertial navigation algorithm as in [11] was adopted. The basic idea is the orientation tracking by integrating the gyroscope measurements. The orientation is needed to align the local accelerometer data in global space to subtract the gravity resulting in the global linear acceleration. By integrating these acceleration values the distance can be estimated. The concrete implementation of these steps can be done in several ways.

Since the used IMUs contain a magnetometer the orientation filter of Madgwick [12] can be applied for the orientation calculation. Madgwick's filter is characterized by a simple implementation and parameter tuning. The filter provides an orientation estimation relative to the direction of gravity and the earth's magnetic field for MARG (Magnetic, Angular Rate, and Gravity) systems, also known as AHRS (Attitude and Heading Reference Systems). With an optimal fusion of accelerometer, gyroscope and magnetometer measurements it calculates a quaternion representation of the orientation.

With the calculated quaternion q the local acceleration acc_{local} can be aligned in global space by quaternion multiplication as in (1) where i is the current time step and q^* the conjugated quaternion. For the resulting global acceleration acc_{global} it is assumed that the z-axis points to the ground and that the x- and y-axes are not affected by the gravity. The error due to the incorrect alignment in global space is neglected.

$$acc_{global_i} = q_i \otimes acc_{local_i} \otimes q_i^* \quad (1)$$

The calculation of the trajectory is done in the x-y-plane only by double integrating the x- and y-accelerometer measurements applying the rectangular method for each time step as in (2) and (3). The integration of the global acceleration data results in the velocity v. By integrating the calculated velocity, the distance s can be estimated.

$$v_i = v_{i-1} + \frac{\Delta t}{2} * (acc_{global_{i-1}} + acc_{global_i}) \quad (2)$$

$$s_i = s_{i-1} + \frac{\Delta t}{2} * (v_{i-1} + v_i) \quad (3)$$

C.! Data Fusion

The synchronization of IMU and camera data can be done with an LED signal emitted by the IMU sensor system. The experiment was recorded by the camera with a framerate of 25 fps. Knowing the height of the persons a 3D position for each frame for both participants was calculated. The IMUs logged data with 100 Hz, so that for four consecutive IMU signals one value extracted with the camera system can be taken into account.

For the trajectory extracted with the camera system the velocity ($v_{cam?@}$) was determined by calculating the distance covered within one second. The positions 0.5 seconds before and after the current time step were used for this purpose as in (4) where Adefines the current time step (or frame). By calculating the difference between the positions 12 frames before and after the current frame the velocity is averaged over 25 frames which is equal to one second.

$$v_{cam?@_B} = \frac{(CoD_{B-1E} F CoD_{BG1E})}{1\ H} \quad (4)$$

The velocity is calculated for the person in the evacuation chair as well as for the pushing one. The velocity of the wheelchair user is needed for the initial alignment of the IMU and camera trajectory while the data of the pushing person are taken into account for restricting the velocity of the evacuation chair.

At first the start heading of the IMU trajectory needs to be aligned with the heading of the trajectory extracted with the camera system for which the coordinate system can be chosen arbitrary. For this purpose, the ground truth data of the person in the evacuation chair are used. It is assumed that participants of experiments with dense crowds are at least visible once for the camera system. Thus, it is a valid approach to use the ground truth for initial alignment. The angle I between the vectors $v_{cam?@_J}$ and $v_{aK?@g?}$ is calculated with $v_{aK?@g?}$ standing for the mean value of the first 100 velocity measurements of the IMU. The accelerometer data are rotated along the z-axis by I with the corresponding quaternion q_L so that (1) is changed to:

$$acc_{global_i} = q_L \otimes q_i \otimes acc_{local_i} \otimes q_i^* \otimes q_L^* \quad (5)$$

v_J from (2) is initialized with the velocity of the wheelchair user calculated with the camera data as in (4). After that v_i is updated as in (2) with the rotated acceleration of (5). For restricting v_i the velocity of the pushing person $v_{cam?@_M}$ is included in the calculations as follows. If the absolute difference Nv_i O $v_{cam?@_M}$Nexceeds a predefined value $v_{@Pg?}$ v_i is set to $v_{cam?@_M}$ It needs to be considered that the indices i and Aare not equal because of the different sample rates.

IV.! Experimental Results

The trajectory of the wheelchair was calculated for different values of v_{QtRST}. Selected trajectory plots are shown in Fig. 3. Due to the velocity resets discontinuities are visible for higher values of v_{QtRST}. For the evaluation of the tracking the number of velocity resets was determined and the average and maximum distance to the ground truth was calculated (see Table 1).

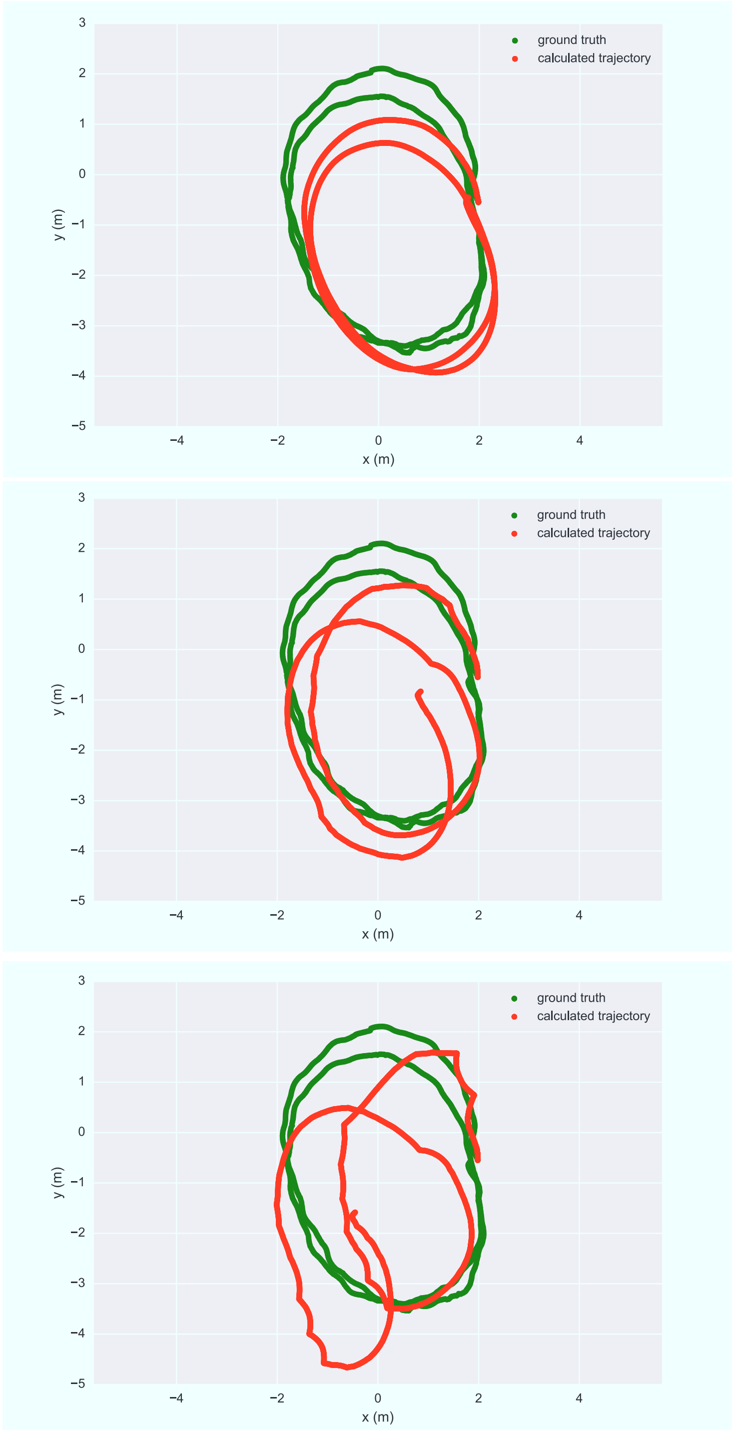

Fig. 3.! Caculated IMU trajectory and ground truth trajectory of the evacuation chair for v_{QtRST} = UWW(top), v_{QtRST} = UWX (middle) and v_{QtRST} = UWU (bottom).

TABLE I. ! COMPARISON OF CALCULATED TRAJECTORIES FOR DIFFERENT VALUES OF $v_{@\alpha Pg?}$ WITH A TOTAL NUMBER OF 4381 VELOCITY VALUES

$Y_{Z[\backslash]^}$ (m/s)	Number of resets		Average error (m)	Maximum error (m)
	Absolute	Relative (%)		
0.01	1601	38.1	0.84	1.50
0.02	824	19.6	0.80	1.48
0.03	559	13.3	0.81	1.51
0.04	380	9.0	0.81	1.54
0.05	307	7.3	0.81	1.49
0.06	254	6.0	0.90	1.61
0.07	208	4.9	1.14	2.53
0.08	183	4.4	1.17	2.52
0.09	159	3.8	1.27	2.93
0.10	137	3.3	1.12	2.57

The quality of the IMU trajectory does strongly depend on the adjustment of the start heading which needs to be improved. A rotation of the curve to the right around the start position would result in a better approximation.

The lower $v_{@\alpha Pg?}$ the better the approximation but the more velocity resets were made which leads to a low consideration of the actual acceleration of the IMU. The slight fluctuation in the error appears because of noisy acceleration measurements which are fed into the position estimation. By reducing $v_{@\alpha Pg?}$ the approximation gets smoother due to continuous resets of the velocity to a smoothed velocity over one second. With $v_{@\alpha Pg?} =$ UWX an appropriate balance between the number of resets and error is achieved. The corrected velocity is shown in Fig. 4. Since the velocity of the pushing person is used for the reset a shift of the data along the time axis is visible. This needs to be improved at a further stage.

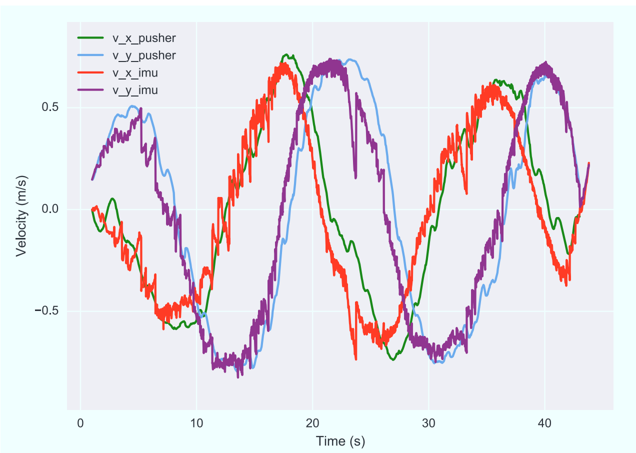

Fig. 4.! Velocity of the evacuation chair (ground truth) and corrected velocity based on data of the IMU and pushing person.

V.! CONCLUSION AND FUTURE WORK

A hybrid tracking approach fusing data of a camera detection system and IMUs was investigated. The main focus is the gapless tracking of wheelchair users in dense crowds which are getting occluded by surrounding people. It is possible to track the wheelchair with a maximum distance error of 1.5 meters for 43 seconds by restricting the velocity of the wheelchair with the velocity of the pushing person.

In future work the fusion of IMU data of multiple sensors attached to the wheelchair will be examined. Besides the fusion with data of multiple surrounding persons will be analyzed. As an additional restriction of the IMU trajectory the distance between the wheelchair and the pushing person can be constrained and adjusted. Means should be found to improve the position estimation based on the noisy acceleration measurements. Different algorithms for orientation estimation and data fusion approaches will be investigated, such as the Kalman Filter.

ACKNOWLEDGMENT

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