Concept of autonomous vehicle control and data acquisition

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Abstract. A concept of an autonomous electric vehicle with human/object following capability and obstacle avoidance is proposed in this paper. The vehicle considered is a four-wheel vehicle with rear-wheel drive and front-wheel steering. This vehicle uses ultra-wideband technology for human/object detection and position calculation. Unlike computer-vision-based approaches, ultra-wideband technology is insensitive to variations in illumination, does not impose the direct-line-of-sight requirement, and the underlying data processing algorithms are simple. The output from the ultra-wideband system is used by a bidirectional (both forward and reverse motion) human/object following control system based on the classical PID control approach. Since the ultra-wideband object localization works even if there are obstacles between the vehicle and the object to be followed, an obstacle avoidance system is necessary. This requirement is handled in the proposed concept by lidar sensors and integration of the vector field histogram algorithm into the structure of the human/object following control system. The performance of this concept was tested using a small-scale (mass ca 70 kg) experimental autonomous vehicle with encouraging results.

Keywords: Autonomous vehicles, Object following control, Obstacle avoidance, Ultra-wideband technology.

1 Introduction

Vehicles with various degrees of autonomy play increasingly substantial roles in numerous areas of human activity. These vehicles must interact with humans or other vehicles in many applications. A specific and basic form of such interaction is the automatic following of humans or, more generally, of other moving objects. This person/object following behavior is essential in industrial applications as well as in many spheres of everyday life, in particular as a part of various assistive technologies.

Any automatic object following system must perform two basic operations. First, detection and calculation of the position and orientation of the target object . Second,

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object following control aiming at keeping the specified distance between the vehicle and object to be followed.

The task of object detection and position calculation is most commonly handled by vision-based algorithms, such as the algorithms described in [1-2]. This fact is also stated in the review paper [3]. The availability of relatively low cost high quality cameras and significant developments in the field of computer vision algorithms are the main factors contributing to the popularity of vision based methods. However, these methods also have some substantial disadvantages. The precision of object position calculation is negatively affected by camera calibration errors and changes in illumination. The demands on computer power are also relatively high and this limits the applicability of vision-based methods in cost sensitive real-time applications. Moreover, there must always be a direct line-of-sight between the vehicle and the object to be followed. This requirement makes these methods sensitive to disturbances if this direct-line-of-sight is even temporarily interrupted.

In this paper we propose a human/object following system based on ultra-wideband (UWB) technology. This technology (see [4] for a survey) has now reached a significant degree of maturity, and it has several significant advantages. The requirement of direct-line-of-sight is removed, localization is fairly precise regardless of variations in illumination and the complexity of algorithms for processing UWB measurement data is low.

The use of UWB technology for human/object following has already been proposed in several recent papers, most notably in [5-7]. However, it was used for simple following of an object moving in front of the vehicle. In some papers [7] it was also combined with a camera to improve the certainty of detection of the human operator to be followed.

The objective of this paper is to go several steps further beyond the published results available in the literature. The system described in the present paper is bidirectional, i.e., it follows the person or object but it can also move in the opposite direction if the person or object starts moving backwards. Further, the fact that UWB technology does not require that there is a direct-line-of-sight is an advantage of UWB over computer-vision. However, it can also happen that there are obstacles between vehicle and object or human to be followed. Unlike computer vision, UWB is not able to perceive such obstacles. For this reason 2D lidar sensors are used and their measurements are input to an obstacle avoidance algorithm. This obstacle avoidance algorithm is integrated into the human/object following control system.

2 Experimental autonomous vehicle

The concept described in the next sections of this paper was tested using an experimental vehicle. This vehicle can be characterized in the following way. It is four-wheel vehicle with rear wheel drive and front wheel steering. Front wheel steering of is driven by two independent servo motors. Although this feature is not used in the present paper, this concept of two independent servos enables software emulation of different steering geometries. The rear wheel is driven by a DC motor that allows forward and reverse movement at variable speeds. The dimensions of this vehicle are: length of about 120 cm, wheelbase of 77 cm, a track width of 67 cm, 13 x 5-6 tires and weight of about 70 kg including a composite car body. This experimental vehicle is shown in **Fig. 1**

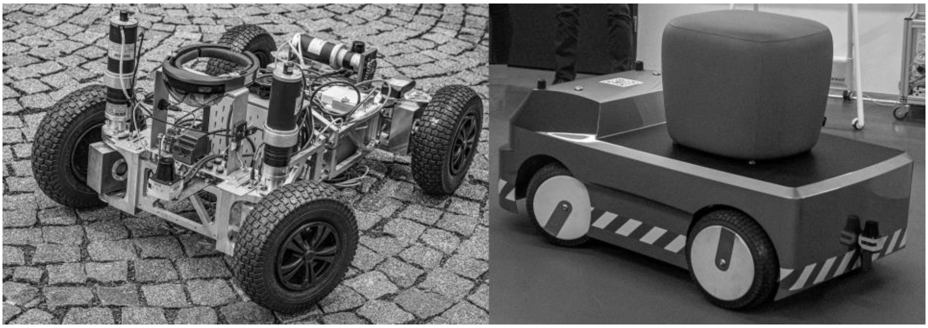

Fig. 1. Experimental vehicle. Left: vehicle frame with wheels, motors, lidars and HoloLens. Right: vehicle with a composite body carrying a load and beacons of the ultra-wideband tracking system.

This vehicle features an UWB tracking systems that can be used for person (or object) following operation. Its operation principle is shown in **Fig. 2**.

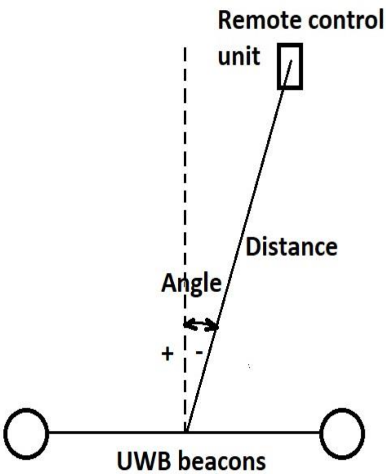

Fig. 2. Ultra-wideband positioning system

It uses two UWB beacons (anchors) located at the corners of the front of the vehicle and a remote control unit with a UWB tag (sensors produced by Terabee company). This remote control unit is attached to the object to be followed or it is carried by the followed person. The beacons are visible in the right part of **Fig. 1** in the front part of the vehicle. Two-way ranging (TWR) between the beacons and remote control unit is performed in regular intervals. The output from TWR is the measured distances between the beacons and remote control unit. These two measured distances together with known span between the beacons are then used to compute the distance and heading angle of the remote control unit with respect to the central point between the two beacons.

The obstacle avoidance system is based on lidars. The lidars used are TIM 781 by Sick (front and rear) with the following characteristics. Sensing range from 0.05 to 25 m, field of view within ±135° from the forward axis of the sensor with 1/3° angular resolution (i.e., the output of each individual scan is an array of 811 values) and maximum scan rate of 15 samples per second. Useful field of view of the lidars is limited by vehicle construction to ca ±90°, because of the positions of vehicle wheels.

The last sensor with a less obvious purpose is the Microsoft HoloLens device. It is built into the front of the vehicle and integrates several sensors: Inertial Measurement Unit (IMU, i.e., accelerometer, gyroscope, magnetometer), depth camera and HD video camera. Although HoloLens device is primarily intended to be used as an augmented reality device, the information from its sensors can also be utilized to obtain the information about vehicle position even in the indoor environment where signal from satellite navigation systems is not available. In the current implementation, software is running on HoloLens device and it periodically (period ca 50 ms) calculates the current position of the device (relative to the place where the software is started), namely Cartesian coordinates and rotations. This information can be utilized by the on-board control system and/or sent to a higher level supervisory system via Wi-Fi network.

PLC by B&R is used as an on-board control system. One of the reasons for this choice is the availability of Automation Studio Target for Simulink. This software enables easy and fast programming of PLC from Matlab/Simulink environment.

Using this set of sensors, the vehicle can be operated in two basic modes of operation.

1. Autonomous driving mode from point A to point B with a predictive controller providing passage along a predefined trajectory or an optimized trajectory given obstacles and space constraints between predefined points A and B. In this mode HoloLens device is the main sensor used to get the current position information. This variant of control was outlined in [10] and it will not be discussed in the present paper. However, even if the position from the HoloLens device is not used for control it is used for monitoring purposes in the Ante Web application that will be described later in the present paper.

2. Intelligent tracking mode of another object/person where the main sensor is the ultra-wideband tracking system and lidars are used for obstacle avoidance. This is the main topic of the present paper.

3 Bidirectional human/object following control with obstacle avoidance

3.1 Human/object following control

The output from the UWB system is the distance and heading angle of the remote control unit. The function of following can be interpreted as a feedback control task where the two controlled variables are distance and heading angle, while the two manipulated variables are vehicle speed and steering angle. The objective is to keep the distance at a specified set-point value, while the heading angle should be zero because it actually plays the role of an angular deviation between the current and desired direction of the vehicle motion.

A classical method for building formations of mobile robots is the virtual spring damper approach [9]. It can be used to create larger swarms of robots as well as simple formations with one leader and one follower robot. In this approach there is virtual force acting on the follower robot (vehicle) which is proportional to the displacement and the relative speed between the ends of the springs

$$F(t) = k_R\big(d_0 - d(t)\big) + c_R \frac{d}{dt}\big(d_0 - d(t)\big) = k_R e(t) + c_R \frac{de(t)}{dt} \tag{1}$$

where k_R is the virtual spring stiffness coefficients, c_R is the damping coefficients of the virtual damper, $d(t)$ is the current spring length (i.e., the distance between the vehicle and object or human to be followed) and d_0 is the resting spring length, i.e., the distance set-point. That means it has proportional derivative (PD) behavior with force as an output. Considering that force can be expressed using the Newton's second law as $(t) = m\frac{dv(t)}{dt}$, equation (1) can be interpreted as a proportional integral (PI) controller with vehicle speed $v(t)$ as controller output, i.e., as a manipulated variable.

In accordance with this, PI controller based on the difference between the distance measured by UWB sensors and distance set-point is used to control the distance using vehicle speed as a manipulated variable. Another PI controller is used to control vehicle steering angle using the measured heading angle as a control error (angle set-point is zero). It was, however, shown by practical experiments that integral term does not improve the control performance, but rather results in unnecessary control oscillations. For this reason, simple proportional control was eventually used for both the vehicle speed and steering angle control.

This concept was first tested on a pure following task where the vehicle follows an object or person in front of it. In this form the control worked, however, if the object/human to be followed reached a point where there was no space to turn on a circle corresponding to the turning radius of the vehicle and the vehicle followed it, the following control had to be switched off and the situation had to be resolved by other means. For this reason, the control was extended so that the following become bidirectional. Thus, if the vehicle approaches the tracked object too closely, it will start to move backwards to keep the distance at the specified set-point. In the event that the tracked object cannot turn around, it can thus "push" the vehicle back.

This extension required some change in how the control system evaluates the distance control error. If the distance were regulated to a constant value even with the ability to move backwards, the vehicle would tend to periodically move slightly forwards and backwards even when the object or human to be followed is standing.

The cause of this phenomenon is in the UWB measuring system where the measurement results fluctuate to some extent even if both the tracked object and the vehicle are standing. For this reason, a certain deadband is introduced into the control to stop the vehicle and prevent it from unnecessary random movements. If the magnitude of the control error is less than deadband vehicle speed is zero.

3.2 Lidar based obstacle avoidance

Vehicle instrumentation includes two TIM 781 lidars located at the front and rear of the vehicle as described in section 2. The data from these lidars are used for several purposes. The basic functionality is emergency stop if the vehicle gets too closely to an obstacle. This is a very simple functionality, and it follows up on preliminary lidar data preprocessing. The lidars generate zero or very small values in the directions where the obstacles are so far away that they cannot be detected (i.e., more than 25 m, but if it is a black surface, there may be a problem with detecting significantly closer obstacles). These nonsense values must be removed and it is also necessary to remove the values in the directions where lidar view is affected by vehicle wheels.

The distance of the obstacle can be easily determined from this pre-processed data, and the vehicle will automatically stop if this distance falls below a specified threshold. Since the actual vehicle speed follows its set-point with a certain lag (first order dynamics with time constant about 0.25 seconds in the case of the experimental vehicle considered in this paper) this threshold value is changing with the vehicle speed.

UWB technology provides angle/distance data even if there is no direct line of sight between the vehicle and the object to be followed. If the control were based just on this angle/distance information, the vehicle would move regardless of the existence of obstacles and eventually it would be stopped by emergency stop. For this reason, obstacle avoidance mechanism based on the vector field histogram plus (VFH+) algorithm [10] was included to the control structure. VFH+ algorithm computes obstacle-free steering directions for a vehicle based on lidar readings. It considers the vehicle size and minimum turning radius while computing the obstacle free directions from lidar readings. The final choice of the steering direction is based on a cost function that evaluates how close the different candidate directions are to the target direction and to the current and previous directions of the vehicle.

Hence, VFH+ algorithm can be used in such a way that heading angle from the UWB system is the target direction, in which the vehicle should move in order to track the followed human/object. If this direction is an obstacle free direction, it is not changed by VFH+ algorithm. If there are obstacles, this angle is modified in order navigate the vehicle into an obstacle free direction provided such a direction can be found. Complete control structure is shown in **Fig. 3**.

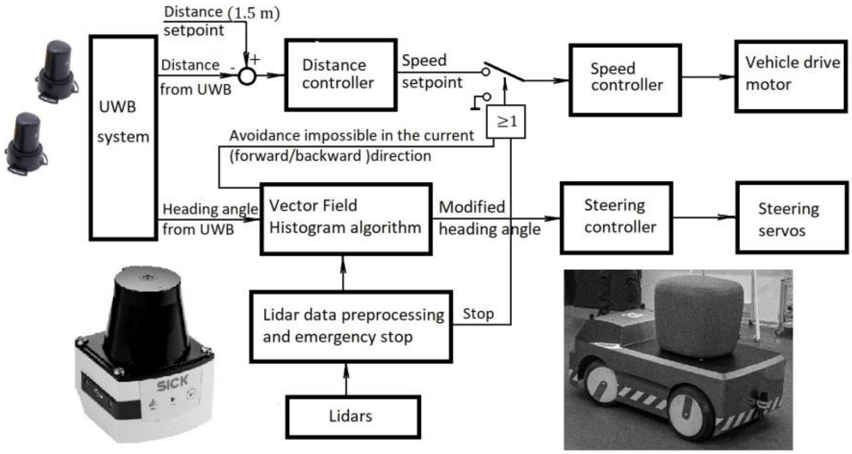

Fig. 3. Structure of the vehicle control system

Corresponding structure of control implementation is shown in **Fig. 4**. This control is running on a B&R PLC system using Automation Studio Target for Simulink, which allows the PLC to be programmed directly from the Simulink environment.

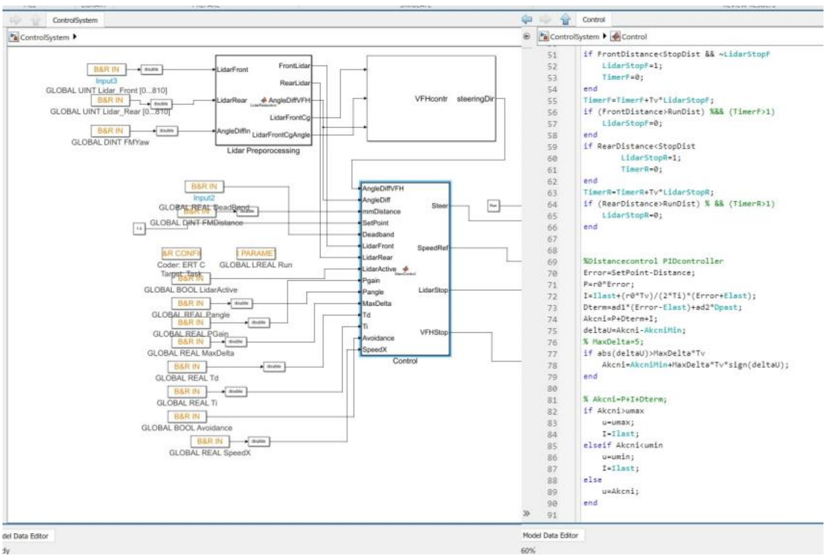

Fig. 4. Structure of the control implementation in Simulink with an example of a part of the code of the control function block

This control system has been thoroughly tested in both indoors and outdoors environments with both static and moving obstacles (walking people). The testing results are promising and the vehicle is able to satisfy the human/object following as well as obstacle avoidance requirements.

4 Data acquisition concept using cloud application ANTE WEB (auto.cxi.tul.cz)

As has been already stated, even if HoloLens device is not used for feedback control, it is used for data acquisition and monitoring purposes. The position data from HoloLens are visualized using web application called Ante WEB. It displays basic data about the vehicle position, movement direction and route in a user-defined map.

In the application it is possible to insert maps and their transformations with respect to the real dimensions of the space where the vehicle will move. The application then displays the position of the vehicle on the selected map and at the same time allows to define the space (virtual walls) for the vehicle movement on the given map, to define the areas in front of obstacles and to display the route between the start and end points, including color differentiation of the route parts according to the direction of movement (forward, backward). Block diagram of Ante web functionality is shown in **Fig. 5**.

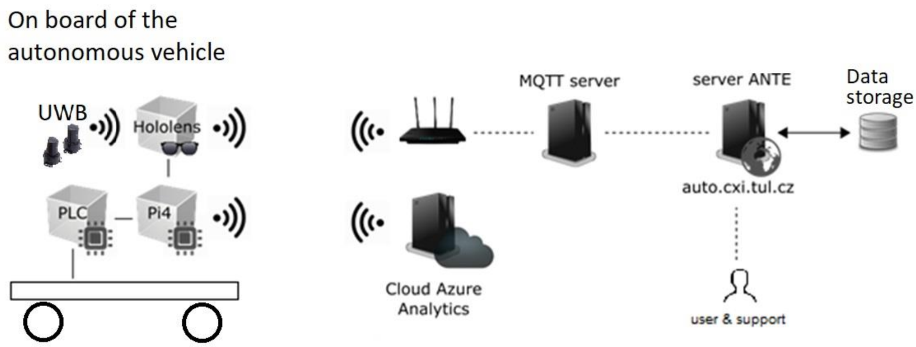

Fig. 5. Block diagram of Ante web system

The web application includes a process that communicates with external elements (mainly with the vehicle) by writing and reading the data from the MQTT server. The data passed through MQTT server include the current location of the vehicle (including its orientation), the route with vehicle directions, obstacles and the defined space (virtual walls). The data is stored on the MQTT server (additionally with a time stamp) and all elements consuming this data can retrieve it at any time (including the ANTE TUL web application). Thus, when the map web page is displayed, the MQTT data is always loaded and the user can see the current dataset (route, obstacles and defined area) that the vehicle is working with. The application allows these objects to be plotted on the map and saved via MQTT on demand, or retrieved from MQTT on demand. Objects can be manipulated in the map by dragging individual points, removing individual points, or removing individual objects from the map.

The maps (images) over which the position of the vehicle is displayed can be inserted into the application on the application user interface and the values for recalculating the real position of the rover to the position on the map can be defined. The initial position of the rover in the map is defined for the conversion (to show the correct position in the map, the rover must always start from this position in the real environment) and a scale in the form of the number of pixels per meter in the X and Y axes.

The application allows the user to receive a stream from the Hololens camera and display it on the user interface. However, this view cannot be used for direct observation of the vehicle movement due to latency in data transmission from HoloLens.

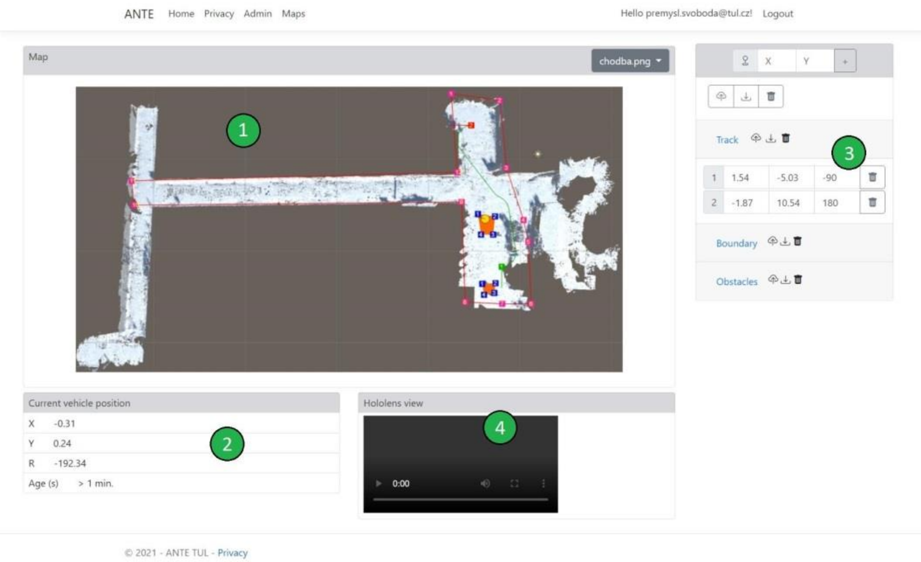

Fig. 6. Main page of the Ante Web application: 1. Map, 2.Current vehicle position and rotation, 3. Object definitions - start and end point of a route, defined areas of movement and obstacles 4. HoloLens camera preview

5 Conclusions

A concept of an autonomous electric vehicle with human/object following capability and obstacle avoidance was described in this paper. This description was accompanied by an outline of a data acquisition application for monitoring vehicle movement. The control system using ultra-wideband technology for object following and lidar sensors for obstacle avoidance has been implemented on the on-board PLC and practically tested with encouraging results.

6 Acknowledgement

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