

A Leader-path-following Formation System for AGVs with Multi-sensor Data Fusion Based Vehicle Tracking

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Abstract. Caravans composed of vehicles with different functionality or trafficability raise the demand that formation system structure shall allow vehicles to deviate from the path to be followed when necessary. In this paper, a formation system is developed for autonomous ground vehicles (AGVs) who follow the path of a leader vehicle while retaining the ability of deviation from the reference path. In addition, it improves robustness of preceding vehicle localization by fusing Lidar tracking, camera tracking results with predecessor's global position within an extended Kalman filter (EKF) in case that one or more sources of preceding vehicle localization is not reliable. The system is applied on real AGV platforms and won the 3rd place in an AGV competition in China.

1. Introduction

During the past decades, formation control has received a lot of attention since it enables coordinated traversal of roads for multi-vehicle system. Techniques from adaptive cruise control (ACC), coordinated ACC (C-ACC) to advanced vehicle platooning has brought much benefits to transportation in fuel consumption, labour costs, traffic throughput and driving safety. Much of the work [1-6] in this area utilizes vehicle to vehicle (V2V) communication technique to transmit information about local control manoeuvres among caravan members so as to reduce inter-vehicle distances and decrease air drag. The results can be remarkable when vehicles in caravan share similar kinematic and dynamic characteristics because manoeuvres from preceding vehicle can be a good reference for its follower. But in many situations, a caravan may be composed of vehicles with different functionality or trafficability. In these cases, more flexible spatial constraint is required for each follower to guarantee safety and functionality. Vehicle with lower trafficability (e.g. vehicles with low chassis) may have to avoid collisions while others (e.g. all-terrain vehicle) need not.

Another group of work [7-13] on development of local control strategy is done to overcome the difficulties when only local positioning and range information to neighbouring vehicles are available. Vehicles normally maintain a formation with rigid configuration in these systems. Obstacles presenting between neighbouring vehicles are not considered.

In this paper, a formation control system is developed to achieve a caravan composed of multiple autonomous ground vehicles (AGVs) who follow the path of the leader vehicle. Follower vehicle can deviate from leader path for collision avoidance purpose. The system obtains robust preceding vehicle localization information by utilizing vehicle tracking techniques fusing Lidar, camera and GPS with an



extended Kalman filter (EKF). This work is an extension based on our prior work [14] where a motion planner is implemented to drive an AGV along given road points. The AGV equipped with our formation control system presented in this paper won the 3rd place in a native competition on autonomous logistics convoy (figure 1) [15].



Figure 1. Our AGV (left) is following the leader vehicle (right) during a native AGV competition.

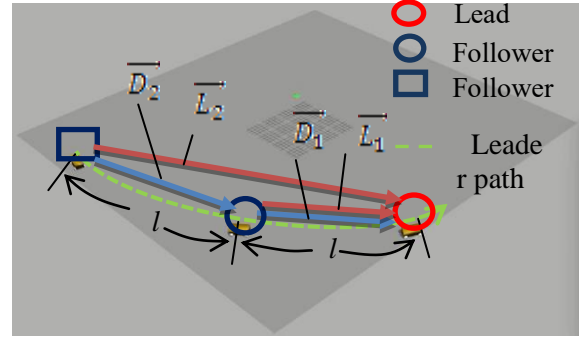


Figure 2. The definition of a leader-path following formation

Similar formation control implementation can be found in [16] where a road-following approach coupled to a tightly constrained route to be followed is presented. It enables deliberative deviation from the route for collision avoidance. The work is validated in simulation. The acquisition of accurate preceding vehicle state is not issued which is challenging in natural environment.

There are two novel contributions implemented in this work: first, a leader-path following formation system is designed to allow follower vehicles with different kinematics or trafficability to follow the leader vehicle's path with necessary lateral and longitudinal motions; second, a vehicle tracking module fusing GPS, Lidar and mono camera data with extended Kalman filter is developed for each follower to localize the preceding vehicle robustly.

The rest of the paper is organized as follows: in section 2, the formation control framework is overviewed first, followed with the generation of path-to-be-followed for each caravan member. The preceding vehicle tracking method is described in section 3 which gives a robust estimation of leader pose and distance to be kept even in severe situation where one or two sensor sources are not reliable. The simulation and experimental results on real platforms are introduced in section 4.

2. Leader-path-following formation control

In a leader-path-following formation, all the followers tries to follow the path that leader vehicle has passed. Comparing with controlling ego vehicle respect to its predecessor's current pose or passed pose sequence, leader-path following guarantees all the vehicles follow the same reference route, so that control error from one vehicle does not propagate to its successor [17].

2.1. Problem formulation

The leader-path-following formation mode implemented in this paper is indicated in figure 2. The leader vehicle is circled in red with its history path LP^* indicated with green dashed curve. Each follower i estimates the leader's state at time t as $L_i(t)$ in its local coordinate, which is defined as:

$$L_i(t) = (\Delta x_i(t), \Delta y_i(t), \Delta \theta_i(t)) \quad (1)$$

where $(\Delta x_i, \Delta y_i, \Delta \theta_i)$ is the pose of the leader in follower i 's local coordinate. Except for the first follower right after the leader, $L_i(t)$ may not be able to be directly measured by Lidar and camera due to occlusion. In order to make full use of visual and Lidar information, $L_i(t)$ is calculated by:

$$L_i(t) = L_{i-1}(t) + D_i(t) \quad (2)$$

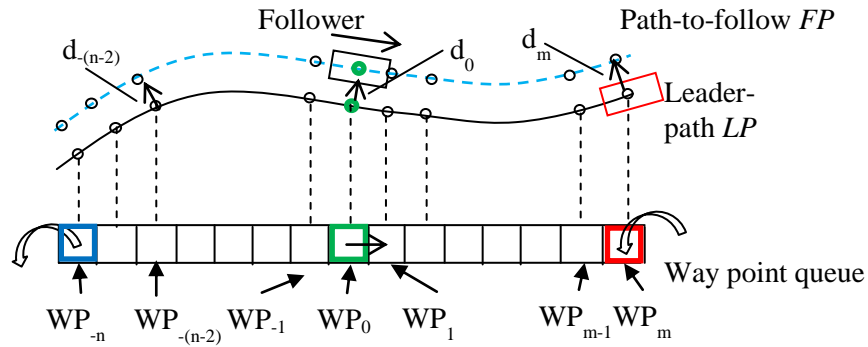


Figure 3. Way point queue and path-to-follow generation.

where $D_i(t)$ (indicated in blue) is pose of preceding vehicle observed from ego vehicle also defined as a triplet of position and orientation difference the two neighboring vehicles. With ego pose data $P_i(t)$ in a fixed coordinate C_i (either world coordinate or odometry coordinate) obtained from INS, each follower maintains an estimated *leader-path* LP_i

$$LP_{i,t_0 \sim t_1} = P_i(t) + L_i(t)|_{t_0 \sim t_1} \quad (3)$$

of leader path $LP^*_{t_0 \sim t_1}$ from leader position at t_0 to position at t_1 in C_i as its reference path to follow. The curve length along LP_i between follower i and $i-1$ is denoted as l_i . Note that each follower maintains a separate leader path LP_i is necessary when it is not perfectly self-localized. This is a common case in situation where global localization system is not accurate due to multi-path reflection or signal block or odometry on different followers have different precision. The error between LP^* and LP_i has to be limited in a reasonable small range for the system to run normally.

Now the formation control of each follower can be divided into two sequential sub-tasks: first, maintain an estimated leader-path LP_i and generate an FP_i as path-to-follow; second, control each follower to move along FP_i while keeping safe distance from preceding vehicle.

2.2. Path-to-follow generation

In this work, path is represented as sequence of way points. For each follower, a queue of waypoints

Algorithm 1. Maintenance of estimated leader-path LP_i and path-to-follow FP_i

1. **Input:** current leader pose WP_m , ego pose P , current gear G , lateral offset d_k
 2. **forever do**
 3. **if** $\|WP_m - WP_{m-1}\| > \text{Min_step_len}$
 and $m < \text{Max_forward_waypoint_num}$ **then**
 4. $LP.\text{push_back}(WP_m)$
 5. Search in LP for the respect way point of P and marked as WP_0
 6. **if** $\text{Max_backward_waypoint_num} == n$ **then**
 7. $LP.\text{pop_front}(WP_{-n})$
 8. **if** $G == \text{Backward_gear}$ **then**
 9. remove $\{WP_k\}_{k>0}$
 10. **return** $FP = \text{reversed } \{WP_k\}_{-n \sim 0} + \{d_k\}_{0 \sim n}$
 11. **else**
 12. **return** $FP = \{WP_k\}_{0 \sim m} + \{d_k\}_{0 \sim m}$
-

$\{WP_i\}_{-n \sim m}$ is maintained as the ego-estimated leader-path LP as depicted in figure 3 and Algorithm 1. In each iteration, a new way point WP_m (indicating the current pose of leader in red rectangle) is

pushed into the end of way point queue when leader vehicle (red rectangle) is observed to have moved more than Min_step_len forward from last way point WP_{m-1} (line 3 to 4). When leader vehicle is too far away, point will be added. The algorithm then gets current poses P of ego vehicle and searches for the corresponding way point WP_0 in the queue (line 5). The details of this searching process is explained in our prior work [14]. To enable backward moving, this queue also stores passed way points with capacity of $Max_backward_waypoint_num$ (line 6 to 7). Since backward moving happens when formation needs to go back to the fork in a road and choose another branch, forward queue $\{WP_k\}_{k>0}$ is emptied. The path FP for ego vehicle to follow is generated by add a sequence of lateral offset $\{d_k\}$ to LP . The offset d can be used to control the relative position between ego and preceding vehicles. For example, let d equals to the lane width will lead the two vehicles to run in different lanes of a road. It is also possible to apply smoothing or other optimization over LP for followers of different kinematics.

2.3. Vehicle motion control along path-to-follow

Once the path FP_i to be followed by follower i is generated, steering and velocity of ego vehicle are controlled to follow FP_i and keep a safe distance from preceding vehicle. A motion planner for UGV is implemented in our prior work [15] controlling ego vehicle to move along FP_i without collision. For formation control task presented in this paper, a PID controller (see equation 4) is applied to guarantee safety with preceding vehicle. This controller tries to keep a constant distant l^* along LP (l and LP are depicted in figure 2) from predecessor who is running at a speed of v_p . The actual ego speed v_e is measured by odometry as feedback. The actual distance l from ego to its predecessor is returned by calculating the curve length along LP_i based on relative pose \vec{D} . The motion planner of the UGV accepts v_E as target speed and controls actuators accordingly:

$$v_E = PID(l - l^* + k(v_p - v_e)) \quad (4)$$

3. Preceding vehicle tracking

The relative pose \vec{D} of preceding vehicle in ego coordinate as formulated in equation (2) in chapter 2.1 is obtained from a preceding vehicle tracking process shown in figure 4. There are 3 sources of preceding vehicle pose data from 3 different types of sensors. Global position, orientation, velocity and acceleration are obtained by integrated navigation system (INS) on preceding vehicle and transmitted to ego vehicle through communication channel. A 3D Lidar (i.e. Velodyne HDL-64E) is mounted on top of the ego vehicle and collect laser point cloud of surroundings. Vehicle detection and tracking algorithm is running on these range data and returns predecessor's state even in poor illumination. A mono camera is also set up in front of the ego vehicle and captures images ahead for a visual tracking process. Images provide more detailed texture information which helps to recognize the desired predecessor from multiple moving objects.

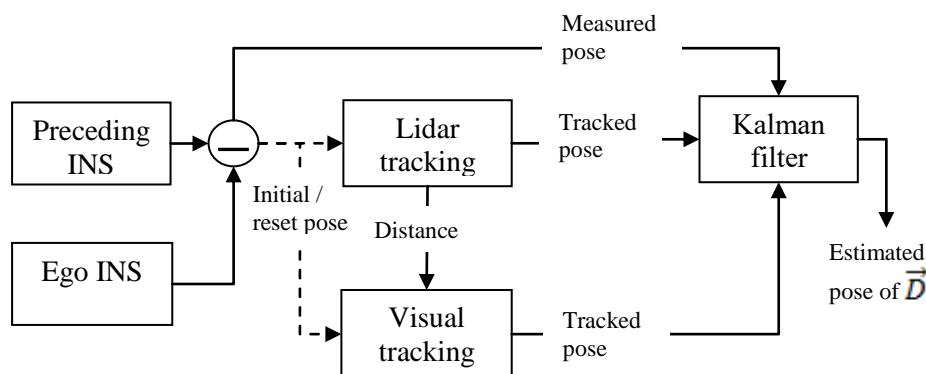


Figure 4. The work flow of preceding vehicle tracking.

3.1. Lidar tracking

The Lidar tracking process (figure 5) is initialized with preceding vehicle pose data (shown as a cyan rectangle in figure 6) received from predecessor. The region of interest (ROI) shown in red is a circle centred at the position of predecessor's GPS antenna. In the ROI, laser point height and gradient of range between laser scans are used to remove ground surface and extract foreground points, i.e. points on preceding vehicle. A hierarchical clustering process is applied to the foreground points. The clustering centre which is nearest to predicted predecessor position in last iteration is selected to be the estimation of current predecessor. The result is both passed to the fusion process and used to do pose prediction for the next tracking iteration. This tracking process runs at a frequency of 10Hz. Uniform linear motion is used as a simple motion model for pose prediction.

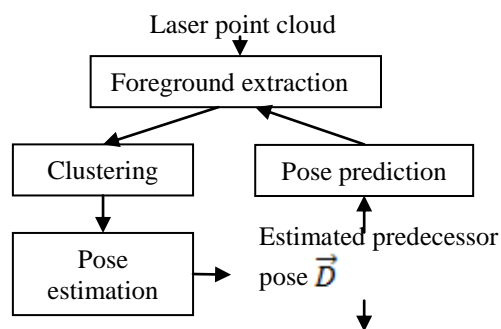


Figure 5. Vehicle tracking process based on Lidar data

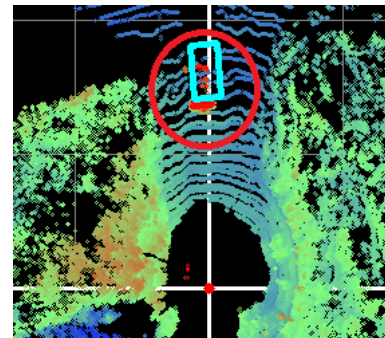


Figure 6. GPS position data (cyan) and searching window for vehicle tracking (red circle)

3.2. Visual tracking

The initialization of visual tracking also gets preceding vehicle pose from inter-vehicle communication. An initial ROI (green square in figure 7) is selected around the initial position according to the texture feature is much less sensitive to illumination conditions than color features. During on-line process, convolutions of feature template and the small windows sampled in the ROI in image feature pyramid are computed. The strongest response (white area in figure 8 right) gives the preceding vehicle position as an initial value for vehicle tracking. In each iteration during the tracking process, a vehicle detector is trained and updated by applying kernelized correlation filters (KCF) [18] algorithm, which speeds up the tracking process a lot. Since range information is not available in 2D images, the 3D Lidar used for tracking is calibrated with the camera and provides corresponding distance.



Figure 7. Visual tracking result (blue) in the initial ROI (green) and the HOG feature template used for detection (right)

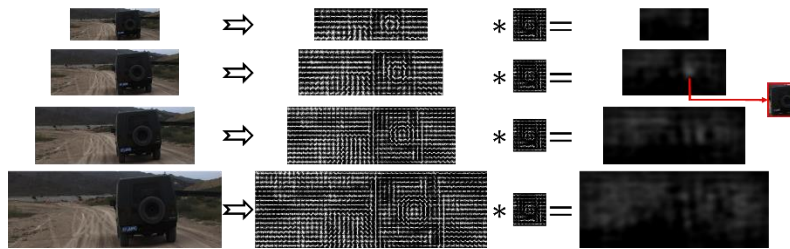
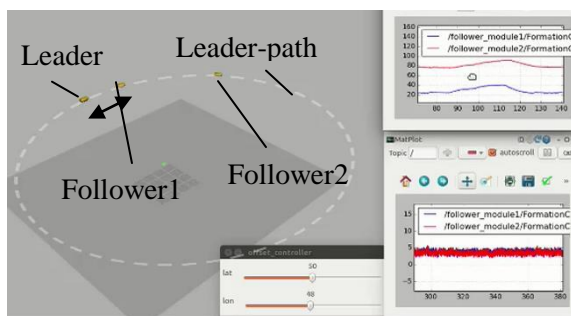


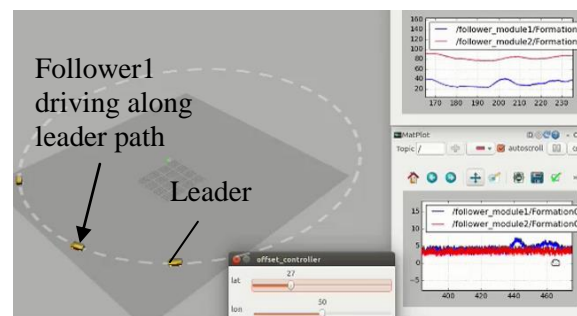
Figure 8. Searching for the strongest response (right) in the image feature pyramid (middle)

3.3. Data Fusion with Kalman filter

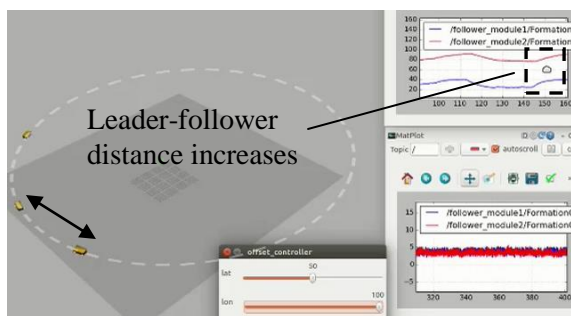
The 3 sources of preceding vehicle localization data are labelled with timestamps and put into the Kalman filter in chronological order. The fusion process is done in a direct EKF scheme [19]. The status of preceding vehicle in the tracking system is defined as a vector $\mathbf{X} = (x, y, \theta, v, \omega)$, with position (x, y) , heading θ , linear and angular speed (v, ω) in odometry coordinate of the ego vehicle.



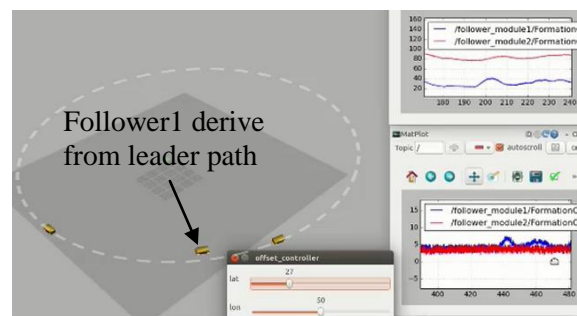
(a)



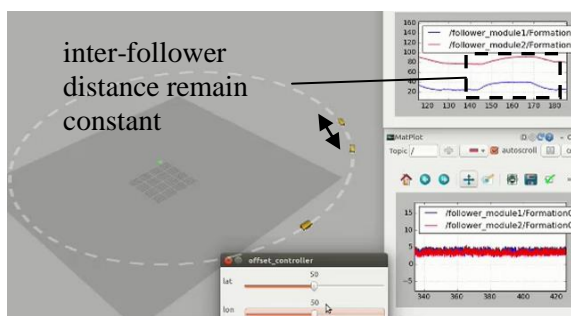
(a)



(b)



(b)



(c)



(c)

Figure 9. Followers keep distance with their predecessors while following the leader path

Figure 10. Deviation motion of one caravan member does not affect its successor

4. Simulation and experimental results

4.1. Simulation result

The simulation is done in an open source simulator called Gazebo [20] which provides high-performance physics engines and ROS based interfaces that can be conveniently accessed. Figure 9 and 10 show the effect on follower when preceding vehicle moves in longitudinal and lateral direction along leader path. In figure 9, the plot at top right corner of each sub figure shows the distance to the leader from two followers (follower 1 in blue, follower 2 in red). The two distances varies together keeping the difference constant. Figure 10 shows that when follower 1 deviates from the leader path (figure 10 (b)), the lateral offset of follower 2 (red plot at bottom right in each sub figure) does not change with follower 1 (blue plot). Please see the video at <https://sqi.cc/c8>.

4.2. Experimental results on real platform

The formation control system developed in this paper is tested on two AGV platforms. A video can be found at <https://sqi.cc/c9>. A one-leader-one-follower experiment is done and the path of two vehicles are drawn in figure 11 with z axis being the data frame count. The path projected to x-y plane shows that the follower path almost coincides with the leader. The time delay between two vehicles is magnified 1000 times along z-axis for a clearer view. The desired gap distance between two vehicles is set to be 30 meters. Actual gap distance (figure 12 up) and the speed (figure 12 down) of two vehicles are visualized. Figure 13 and 14 show two situation where visual tracking is not able to give the correct result. The tracking process can still provide correct localization result thanks to data fusion.

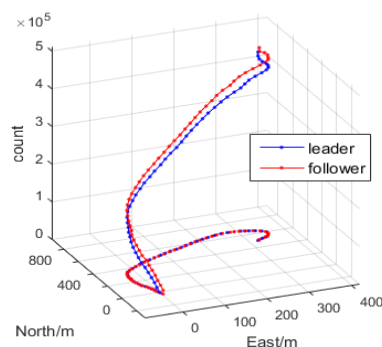


Figure 11. Leader and follower path in x-y-t space

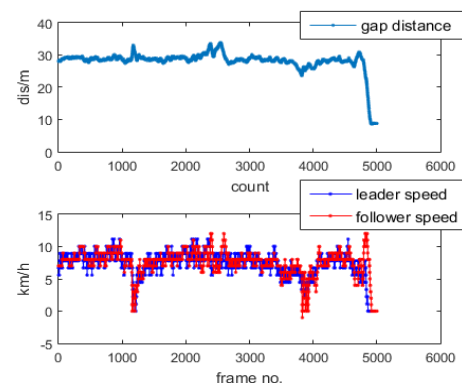


Figure 12. Longitudinal distance and speed difference between leader and follower



Figure 13. Visual tracking result (blue) is affected by the rain while GPS (cyan) and fused result (red) is correct.



Figure 14. Part of the leader vehicle exceeds image border. There is no visual tracking result. But Lidar tracking (yellow), GPS and fused result (red) are still available

5. Conclusion

A formation system is developed to achieve a caravan composed of multiple autonomous ground vehicles (AGVs) who follow the path of a leader vehicle while retaining the ability of deviation from the reference path. The system improves robustness of preceding vehicle localization by fusing Lidar, camera tracking results with predecessor's global position within an extended Kalman filter in case that one or more sources of preceding vehicle localization is not available. Future works include testing on larger scale formations and developing the ability to change formation dynamically with vehicle merging into or splitting from the formation.

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