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GPS-INDEPENDENT AUTONOMOUS VEHICLE CONVOYING WITH UWB RANGING AND VEHICLE MODELS

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ABSTRACT

Leader-follower autonomous vehicle systems have a vast range of applications which can increase efficiency, reliability, and safety by only requiring one manned-vehicle to lead a fleet of unmanned followers. The proper estimation and duplication of a manned-vehicle's path is a critical component of the ongoing development of convoying systems. Auburn University's GAVLAB has developed a UWB-ranging based leader-follower GNC system which does not require an external GPS reference or communication between the vehicles in the convoy. Experimental results have shown path-duplication accuracy between 1-5 meters for following distances of 10 to 50 meters.

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1. INTRODUCTION

To improve safety and efficiency of large vehicles on public highways, there has been interest in using convoys of autonomous vehicles, where a manned vehicle is followed by autonomously controlled vehicles. The navigation, guidance and control of these vehicles is an evolving field.

Many autonomous vehicle guidance systems are dependent at some level on reliable GPS solutions. In GPS-based convoying applications, the path of the first vehicle is recorded by a GPS receiver and "breadcrumbs" are dropped as a desired path for the remaining vehicles in the convoy to follow. Standard GPS solutions are accurate to three meters under most circumstances but can deteriorate due to a variety of geographic or hostile error sources [1]. The solution can be improved using a Real-Time Kinematic (RTK) base station to achieve centimeter level accuracy, but this requires having a nearby base station.

In circumstances with a poor GPS environment or where an RTK base station is unavailable, alternative navigation methods must be implemented. An array of ultra-wideband (UWB) radios positioned on a vehicle in a known configuration can be used to provide a relative position solution between vehicles [2,3]. UWB radios provide a highly accurate range measurement based on two way time-of-flight, TW-TOF, measurements between each node in the network [4]. The ranging solutions vary between UWB modules but often provide centimeter level accuracy up to a few hundred meters.

Auburn University has successfully developed a relative positioning algorithm for ground vehicles using a network of four UWB radios [5]. This paper focuses on a vehicle guidance system which utilizes the relative position estimates to generate and follow a path for autonomous convoys.

2. MOTION MODELING

The control and estimation used in the leader follower system depends on a set of models that define the motion of the vehicles. The independent motion of each vehicle is represented by the kinematic bicycle model, while a relative motion model is used to describe the relative position, movement, and attitude between the vehicles. This section will discuss the derivation and importance of these models.

2.1. Kinematic Bicycle Model

The kinematic bicycle model is a two-wheeled simplification of a full dynamic vehicle model. It relates the steering angle of a vehicle (δ), vehicle wheelbase length (L), and the radius of the path traveled by the vehicle (R). A visual representation of the model can be seen in Fig. 1. The simplification of this model allows for the motion of a ground vehicle to be described with only a few parameters. The model can be used to relate the vehicle velocity (V), steer angle, and yaw rate ($\dot{\psi}$). These kinematic relationships derived from the bicycle model are shown in equations (1) and (2), respectively.

$$\delta = \frac{L}{R} \tag{1}$$

$$\delta = \frac{L\dot{\psi}}{V} \tag{2}$$

If more information is known about the vehicle, the model can be enhanced by incorporating the vehicle understeer gradient. The understeer gradient allows for the model to account for the side slip angles of the vehicle (α_f, α_r) when relating the steering angle to a radius of curvature. This inclusion produces the kinematic equation in equation (3), where $C_{\alpha f}$ and $C_{\alpha r}$ are the cornering stiffness of the wheels on the front and rear axle respectively, and m_f and m_r are the weight distributions to the front and rear axle [6].

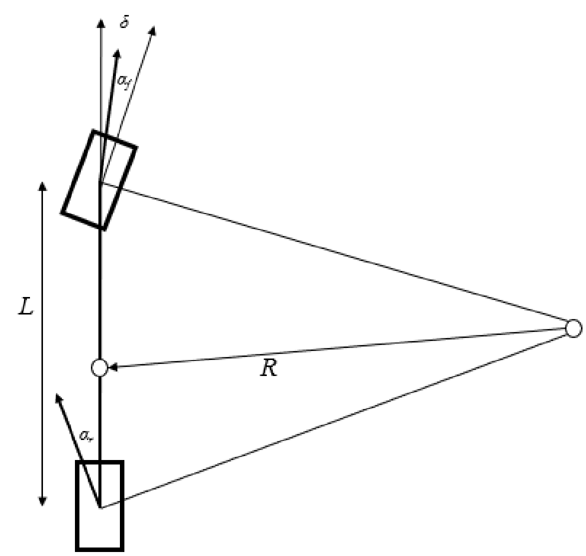

Figure 1: Kinematic bicycle model

$$\delta = \frac{L}{R} + \alpha_f - \alpha_r = \frac{L}{R} + \left(\frac{m_f}{C_{\alpha f}} - \frac{m_r}{C_{\alpha r}}\right)\frac{V^2}{R} \tag{3}$$

The guidance and control system on the follower vehicle was designed for that specific vehicle. Since the vehicle is known to the following controller, the improved kinematic model can be used as a basis for the controller design. In contrast, the estimator was designed such that the system is able to map the path of the lead vehicle without assumptions of the lead vehicle parameters. Thus, a more appropriate state to track is the specific steer angle shown in equation

(4) which does not require the estimator to explicitly know L.

$$\delta_s = \frac{\delta}{L} \tag{4}$$

2.2. Relative Motion Model

For proper path estimation and following, the dynamics describing the relative orientation between the two vehicles should be defined. At a given instant, the 2-D relative orientation of ground vehicles is fully described by three parameters: relative x, relative y, and relative heading. Figure 2 defines the states utilized to describe the relative orientation between the leader and follower.

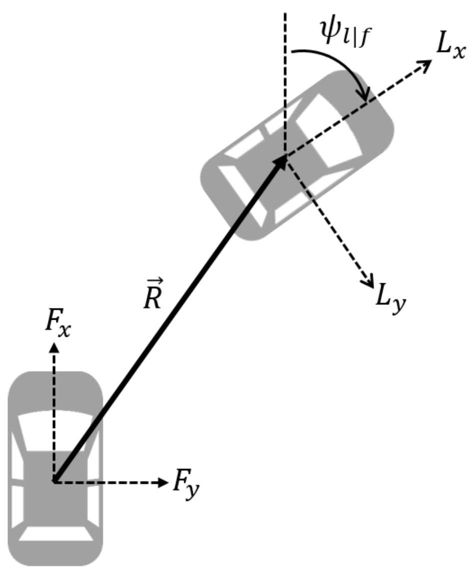

Figure 2: Relative motion model [5]

In the leader-follower scenario, the states are most useful when described in the frame of the following vehicle. The state propagation is dependent on the velocities and yaw rates of each vehicle. The change in relative position between the vehicles is described by equation (5) [5].

$$\begin{bmatrix} \dot{R}_x \\ \dot{R}_y \end{bmatrix} = \begin{bmatrix} -v_{Fx} \\ -v_{Fy} \end{bmatrix} + \dot{\psi}_f \begin{bmatrix} R_x \\ R_y \end{bmatrix} + C_L^F \begin{bmatrix} v_{Lx} \\ v_{Ly} \end{bmatrix} \tag{5}$$

Since the leader velocity is assumed to be measured in its own frame, it must be rotated into the follower frame. C_L^F represents the rotation matrix relating the leader and follower body frames and is constructed with their relative heading. This relative heading is updated using the difference in yaw rates.

This relative motion model aids the path following in two ways. First, it aids the estimation algorithm and allows for the propagation of the most recent estimate during periods of difficult relative geometry or sensor faults. Second, as the following vehicle moves, the previously generated path is updated into its new frame using this model. In an extended convoy operation, this relative motion model may be incorporated on each vehicle with the estimation performed relative to the next vehicle immediately ahead.

3. PATH ESTIMATION

The guidance and control algorithms rely on knowledge of the relative position between the vehicles over time. With no information exchange between the vehicles, the relative position propagation model described in equation (5) contains variables which are not directly measured and thus must be estimated.

3.1 Relative Position Estimation

With ranging data measured between 4 appropriately spaced nodes on the vehicles, the current relative orientation of the vehicles can be estimated at a point in time. The ranges provided by UWB radios are highly accurate, but the range information is not synced between each node in the network. Therefore, direct calculation of the relative position is not feasible at one instance in time. Previous literature has addressed this problem with least squares and Kalman filtering techniques [2,3]. However, with four UWBs, the solution quality is highly dependent on relative geometry of the vehicles. Improvements were made to assist in areas of poor relative geometry through the use of vehicle models in the estimation algorithm [5]. The extended Kalman Filter developed therein is utilized in this leader-follower work with two UWBs horizontally arranged across the roof rack of each vehicle.

The motion models described in section 2 are useful in improving the estimation by providing a method to propagate the current estimate without direct measurements of the lead vehicle's motion. The Kalman filter's process model is constructed from the relative dynamics formulated by incorporating the lead vehicle's longitudinal velocity, V, and specific steer angle, δ_s, in the estimated state vector.

3.2 Path Generation and Mechanization

As the relative position of the vehicles is updated, discrete points are "dropped" for the follower to recreate the path taken by the leader. These points are described by the 2-D relative position estimate at that point in time and are referred to as waypoints. The logic and spacing used to determine when to drop the waypoints vary for the given use-case. An example of a leader path discretized and estimated into waypoints is shown for a static follower case in Fig. 3.

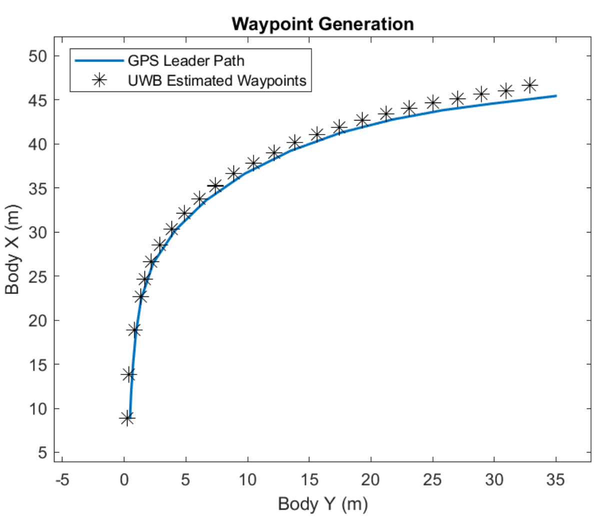

Figure 3: Path waypoint generation

Each waypoint is generated with the current relative position vector - meaning it is only valid with the current position and orientation of the following vehicle. As previously mentioned, the points must be propagated into the new frame of the follower with measurements of the follower's velocity and yaw rate. Equation (5) is utilized with the leader velocity term ignored since the points are stationary. The resulting velocity of the waypoint in the follower's frame may be integrated to generate its updated position. This process must be repeated for each waypoint in the path matrix whenever a follower motion measurement is received. The path estimation is quite accurate while the follower remains static. The main source of path error arises with follower motion due to mechanized errors in the follower motion. The follower's attempt to recreate this path is shown in the results section, Section 6.

4. VEHICLE GUIDANCE

Once the estimator produces a desired path for the follower vehicle to track, the following vehicle's target behavior can be defined. The first step is to select a portion of the path that the guidance algorithm should reference. This is defined by the look ahead parameter, which can be fixed, based on the path characteristics, or based on the speed of the follower vehicle. The guidance software finds the first waypoint on the path that is beyond the set look ahead distance. The path characteristics around this waypoint are used to define the desired following vehicle's behavior.

The vehicle guidance system requires that two characteristics of the path are calculated at the chosen waypoint. The first is the relative position vector (RPV) between the vehicle and the specified waypoint, measured in the vehicle body frame. Second, the angle created by this RPV and the longitudinal axis of the vehicle can be used to define heading error. The heading error (ψ_e) is a measure of how much the follower vehicle's heading needs to change before it is on course to pass through the waypoint. This can be calculated by using equation (6) where x and y respectively describe the longitudinal and lateral coordinate of the waypoint in the follower body frame.

$$\psi_e = \tan^{-1}\left(\frac{y}{x}\right) \quad (6)$$

In addition to information about the relative position of the path, the path's geometry also assists in the vehicle guidance system. Once the RPV to the desired waypoint is found, the vehicle should react differently depending on how the path proceeds immediately after the waypoint, as it may be straight, curve left, or curve right. The calculation of the path curvature is done by analyzing the two waypoints adjacent to the chosen waypoint.

The radius of curvature is a function of the 2 lines that can be created between 3 selected waypoints as shown in Fig. 4. The length of each of these lines (ΔS_1, ΔS_2) are averaged to find ΔS for the selected waypoint in equation (7). The change in the angle of the curve at the selected waypoint can be found by differencing the orientation between the two lines as in equation (8). In equation (9), the ratio formed by these characteristics defines the radius of the path at the selected waypoint.

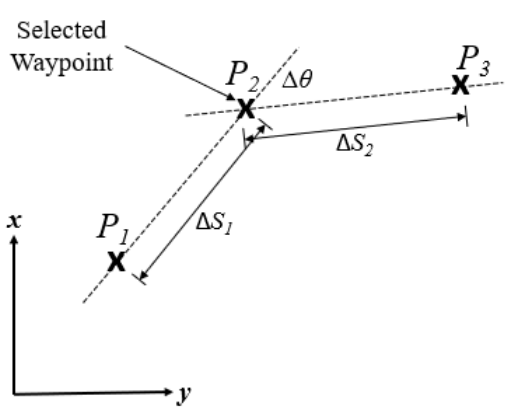

Figure 4: Path curvature calculation

$$\Delta S = \frac{\Delta S_1 + \Delta S_2}{2} \quad (7)$$

$$\Delta\theta = \tan^{-1}\left(\frac{x_3 - x_2}{y_3 - y_2}\right) - \tan^{-1}\left(\frac{x_2 - x_1}{y_2 - y_1}\right) \quad (8)$$

$$R = \frac{\Delta S}{\Delta\theta} \quad (9)$$

4.1. Lateral Controller

The lateral steering controller on the vehicle combines the information gathered by the analysis of the path, with information gathered by the internal sensors on the follower vehicle and the kinematic bicycle model, to produce the steering angle necessary to maintain path tracking. The controller feeds forward a nominal steering angle based on the path's radius of curvature. Using the kinematic bicycle model and understeer gradient, a prediction can be made for the steer angle required to make a turn that has the same radius as the calculated curvature at the target waypoint.

While this feed forward steering is an accurate prediction of what the controller output should be, an additional feedback control equation is used to ensure that the vehicle does not stray from the path due to small errors in this prediction. The feedback control equation (10) is a function of the heading error calculated from the RPV and the measured yaw rate of the vehicle.

$$\delta = \frac{L}{R} + \left[\frac{m_f}{C_{\alpha f}} - \frac{m_r}{C_{\alpha r}}\right]\frac{V^2}{R} + K_p\psi_e \quad (10)$$

5. EXPERIMENTAL SETUP

The path following algorithm has been experimentally verified to work in a real-time application. In order for the following vehicle to autonomously duplicate the leader's path, the algorithm requires measurements from 4 UWB's along with measurements of the follower's motion.

5.1. RR-N 140 NavBox

Robotic Research's RR-N-140 Navigation System, the "NavBox", shown in Fig. 5, is utilized for measurements of the following vehicle's motion [8]. The system can be utilized to generate a navigation solution with an IMU, a wheel encoder, and a GPS antenna. For this GPS-denied experiment, only the wheel encoder and IMU are utilized. As such, no absolute navigation coordinate frame is provided due to a lack of absolute heading reference. However, the NavBox initializes a coordinate frame originating at the startup location and provides velocity and yaw rate with respect to it. This "relative coordinate frame", RCF, is used for the path estimation and mechanization.

Figure 5: RR-N-140 Navigation System [8]

Figure 6: Time-Domain PulsON 440 UWB [9]

5.2. Time-Domain UWBs

Many commercially available UWB modules exist and are sufficient for this estimation problem. Time-Domain's PulsON 440 radios were utilized for this application and are shown in Fig. 6 [9]. The included software allows for ease-of-use in setting up the UWB network and modifying the Pulse Integration Index (PII) to balance the update rate and effective range. The radios were arranged in the 4-node network described in Section 3.1 with a selected PII corresponding to a 15 Hz update rate and 400 meters of effective range.

5.3. Kia/Mkz

The two vehicles used in this paper were a Kia Optima with a human driver and a Lincoln MKZ that is outfitted with an autonomy kit by Autonomous Stuff. The Kia Optima acted as the lead vehicle and carried two UWB radios for the path generation and a GPS antenna to record the vehicle's true path. The Lincoln MKZ carried the remaining sensor suite including the RR-N-140 NavBox and the two other UWB radios. There was an additional GPS reciever mounted to the MKZ in order to record the true path of the MKZ. The MKZ is shown in Fig. 7 with the UWBs along the cross bar and an encoder on the right-rear wheel.

Figure 7: Autonomous Stuff Lincoln MKZ

The autonomy kit on the MKZ works by sending vehicle CAN messages to the MKZ CAN gateway through a ROS interface hosted on a computer in the MKZ. The computer that was used for this is a ADLINK ROScube-X, which manages the path generation, propagation algorithm, and control software.

6. EXPERIMENTAL RESULTS

The UWB-based leader-follower algorithm was implemented using the Robotic Operating System (ROS) via C++ and tested in real-time. The UWB ranges were utilized to generate an estimated path of the lead vehicle while the NavBox's solution propagated it with the follower's motion. Experiments were performed on the skidpad at Auburn's National Center for Asphalt Testing (NCAT) facility. Two runs of the algorithm will be described here. The first test was a follower which recreated a path of the leader after a static estimation period. The waypoints generated in this test were those shown in Section 3.2. The resulting path following with the controller is shown in in Fig. 8. The post-following method results in a following distance of around 50 meters. As was described before, the path degrades with follow distance due to mechanization errors, thus the accuracy of the waypoints becomes skewed as the follower autonomously tracks the path.

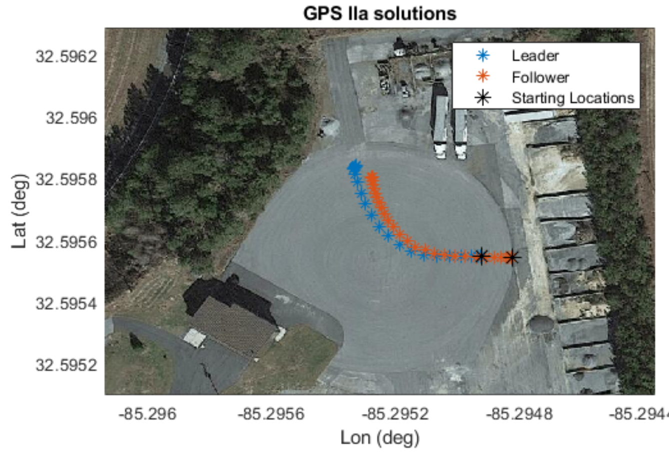

Figure 8: Post-follow path duplication

The resulting error from this post-follow method increased with path length to just under 5 meters as shown in Fig. 9. Note the flat region at the end of the error plots is due to static idling as the follower approaches the final position of the leader and comes to a stop.

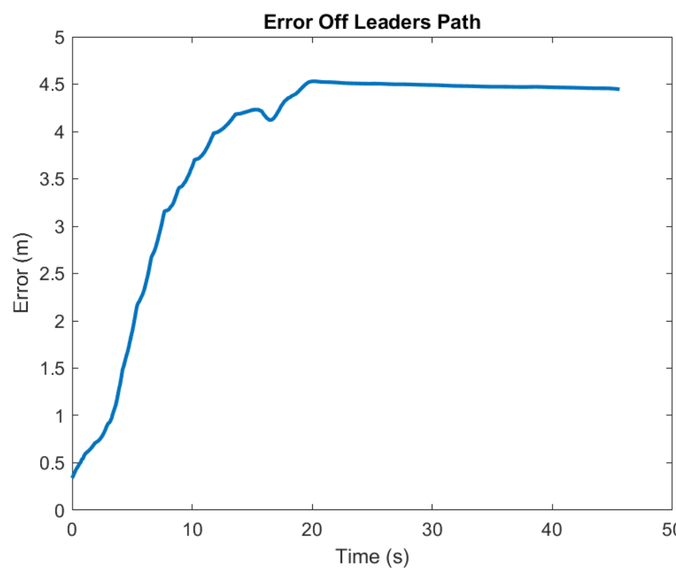

Figure 9: Post-follow path duplication error

With the follower keeping a consistent and closer following distance, the real-time path estimation and propagation is much more accurate. An autonomously-followed path with both vehicles moving simultaneously is seen in Fig 10.

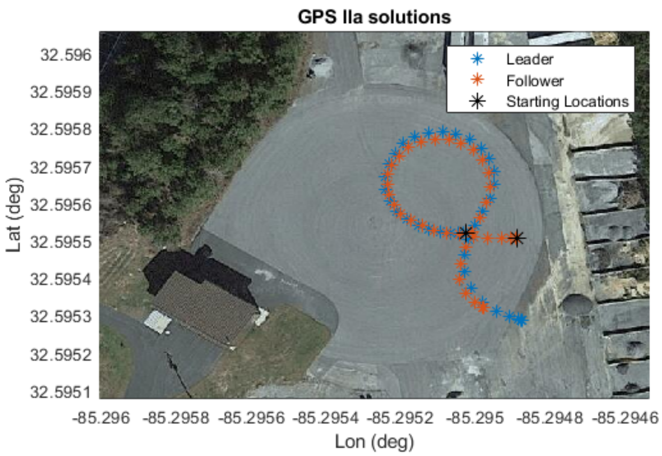

Figure 10: Active-follow path duplication

The errors between the leader and follower paths were calculated beginning when the following vehicle reached the starting location of the leader's trajectory. The errors remain well below the previous test and are quantified in Fig. 11.

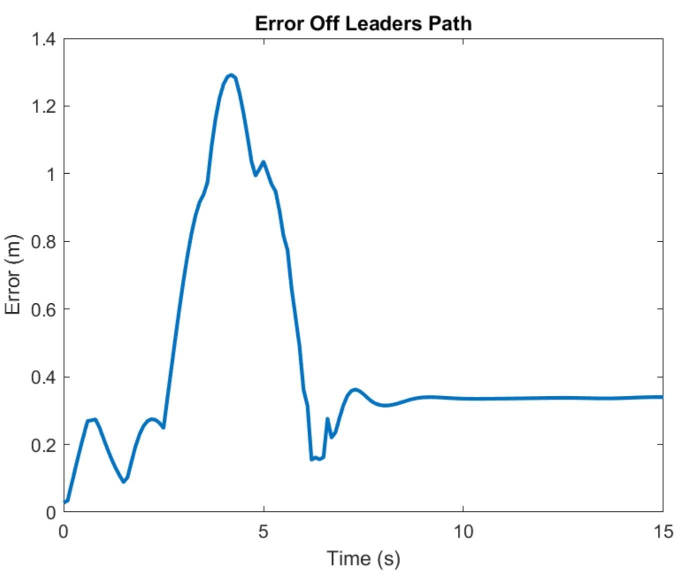

Figure 11: Active-follow path duplication error

There is a key point to highlight in this result. Since each relative position estimate is made in real-time within the frame of the follower, previous path propagation errors do not compound. Therefore, an error estimate of the followed path can be considered independent of the length of time the autonomous following is performed.

7. CONCLUSIONS

It was shown that a path-following algorithm is capable of re-generating the lead vehicle's trajectory using UWB ranging and on-board inertial navigation without a GPS reference or inter-vehicle information exchange. The estimation methodology makes only basic assumptions of the lead vehicle's method of motion. The only *a priori* information required for the estimation is the position of the UWBs with respect to the center of gravity of each vehicle (their respective body-frame origin). The quality of the path generation is dependent upon following distance and relative geometry. Since the UWB estimation algorithm is inherently based in the follower's frame, the path-following errors grow only with following distance and relative geometry, but not with the length of time the algorithm operates.

8. REFERENCES

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