Integrating Vision Derived Bearing Measurements with Differential GPS and UWB Ranges for Vehicle-to-vehicle Relative Navigation

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BIOGRAPHY

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ABSTRACT

In this paper Vehicle-to-Vehicle navigation is reviewed and the augmentation of between vehicle moving base stations differential GPS with ultra-wideband range measurements and vision derived bearing measurements is proposed. A method for deriving bearing measurements from video data is introduced theoretically and then demonstrated. Real data collected with two vehicles driving on a city street in Calgary is then used to demonstrate the method. The initial results show small errors in vision derived bearing measurements. The augmentation of DGPS with vision derived bearing measurements and UWB range measurements shows an improvement in the horizontal navigation solution provided that the range and bearing measurements are free from systematic errors.

INTRODUCTION

Vehicle positioning is an important component of intelligent transportation systems. Due to the relatively low cost and low complexity of Global Navigation Satellite System (GNSS) receivers, the automotive industry has adopted this technology to provide vehicle position. In many current applications, this involves only absolute position, typically at the road level in open sky outdoor environments. However, in various cases, position solutions are needed in urban canyons or under dense foliage where there is poor GNSS availability. Even in some circumstances where a GNSS solution is available, the solution may not be accurate enough for some applications. In these cases, other sensors can be used in order to improve the accuracy of GNSS positioning.

In many applications the absolute positioning solution is not the main interest. Instead, relative positions are required. For example, cooperative driving on highways or safety related applications such as blind spot warning or collision avoidance. In these cases additional sensors can be integrated with GNSS to increase both the availability and the accuracy of the relative position solution. Recently, peer-to-peer (P2P) cooperative positioning has been proposed where peers obtain pseudorange measurements from satellites through their GNSS receivers and use their wireless interface both to communicate with each other and to obtain terrestrial range measurements to other peers. In this method, by fusing these measurements, relative positions can be estimated accurately even when insufficient GNSS
observations are available. Results have shown that P2P cooperative positioning can outperform traditional GNSS-only positioning in terms of both accuracy and availability (Gonzalez et al 2007). In this paper, a similar P2P network using both differential GNSS and direct ranging is demonstrated but with the addition of bearing measurements. In this scenario, the position of one of the vehicle assumed to be known. This vehicle is called “lead vehicle”. Previous work has shown that the absolute position of this vehicle, which is used as a moving base station, does not need to be precise (Tang 1996) and can be achieved using GPS data only.

In cases where two vehicles require a horizontal relative positioning solution in the absence of GNSS measurements, vehicle-to-vehicle range measurement and bearing measurements are required in order to determine a relative position of one vehicle in the body frame of the other. In this work, Ultra-Wideband (UWB) ranging transceivers are used to provide ranges between the vehicles. With range observations only, the orientation of the other vehicle is still ambiguous. In previous studies adding bearing measurements was shown to improve the relative positioning error especially in the across-track direction (Petovello et al 2012). However, these results were based on simulations. In this paper, a vision sensor, specifically a consumer grade video camera, is used in order to extract real bearing measurements.

Vision-based navigation has received increasingly more attention especially when it comes to intelligent transportation. Since cameras are relatively inexpensive, low power and capable of providing information about the positions of multiple objects and obstacles, there is a preference to use them instead of other more expensive sensors. Many research projects have been conducted investigating vision based navigation in several fields like unmanned aerial vehicles, indoor positioning and robot control. The fundamental prerequisite in this step is to determine which features should be extracted and tracked in order to have accurate and available navigation information. Research in extracting good and easy to track features for vehicle navigation systems is currently lacking. In this paper, a marker is located at the back of one vehicle and during the test this marker is detected in each frame based on its specific properties. Some existing methods involve using two cameras to determine a bearing measurement. Although more features and properties such as range, can be extracted by using two cameras, the additional cost, complexity and the problem of managing asynchronous measurements obtained from each camera, have motivated the use of a single camera in this work.

The remainder of this paper is organized as follows. First, the identification and tracking methods are evaluated in order to extract bearing measurements of the second vehicle in the body frame of the camera-equipped vehicle. The estimated bearing measurements are then compared to those obtained from the carrier-phase GPS/INS reference trajectories of the two vehicles in order to evaluate bearing measurement errors. Then these bearing measurements are integrated with the differential GPS and UWB range data and the performances of five different methods of relative positioning: Range and bearing only, DGPS-only, DGPS + range, DGPS + bearing, and DGPS + bearing + range, are compared in terms of positioning error and solution availability. The bearing measurements obtained from the reference trajectory are also applied to draw a comparison between expected and real improvements resulting from adding bearing measurements.

Bearing Measurements

Most generally, a bearing angle is a horizontal angle measured in an arbitrary frame. In this work, it is defined as the angle between two vehicles as measured in the body frame of one of the vehicles. The angle is measured clockwise-positive from the forward direction axis of the measuring vehicle. In Figure 1 $\beta_{ab}$ is the bearing measurement from vehicle a to vehicle b.

![Figure 1: Bearing Measurement](image)

It is important to mention that in order to relate bearing measurements to GPS measurements the azimuth of measuring vehicle has to be known. In this paper, the IMU data is used for this purpose. However other methods could be used. These include GPS velocity, onboard sensors (compass and/or steering angle sensors), or differential odometry. Additionally, in scenarios with three or more vehicles the azimuth can either be considered as a state to be estimated, or multiple bearings measured by one vehicle can be differenced to form
horizontal angle measurements involving three vehicles. This was simulated in (Petovello et al 2012), however in the current work only the two vehicle scenario is considered.

VISION DERIVED BEARING MEASUREMENTS

In order to derive bearing measurements from one car to another based on image data, it is necessary to detect the target car in each frame. Many approaches can be used for this purpose depending on the feature chosen for tracking. In this paper, yellow rectangle marker, shown in Figure 2 is tracked, though in a practical system other features, for example windows, license plates, tail lights or the entire car, would need to be used.

The marker has two important properties. First, it is yellow. Therefore a yellow mask can be used in order to remove background and other undesired objects from the images. Second, its shape enables the use of morphological operations in order to remove other objects with the same color. The steps involved in the development of algorithm are given in Figure 3. Each step is described in the following.

Calibration of Camera and Undistorting the Image

Since the ultimate purpose of the image processing part is the angle measurement it is very important to compensate for distortions caused by the lens of camera. Hence the first step is to determine the distortion coefficients and undistort the image. In this paper, a MATLAB calibration toolbox developed by Bouguet (2010) is used. The calibration procedure involves taking multiple photographs of a checkerboard pattern. By providing the dimension of squares in the checkerboard, toolbox is able to compute the distortion coefficients, focal length and the principal point. By adopting these parameters, images were undistorted and got ready for further processing.

Yellow Color Mask

Yellow mask is designed. To design this mask, several video frames of the target were converted from RGB to HSV which is more suitable for color image processing and then a yellow range was selected for a range filter (Bradski & Kaehler 2008). The result of applying the filter to one frame of test-data is shown in Figure 4. Note that other objects may have colors in the yellow range. Therefore, before finding the center of mass a region of interest is defined using following steps and then the center of mass was determined in that region.

Figure 2: Marker in Test

Figure 3: Deriving Bearing Measurements Procedure
Figure 4: Results of Applying Yellow Mask (the marker is magnified in right corner of picture)

**Defining Region of Interest**

**Edge Detection**

The shape of the marker can be considered as the second clue for marker recognition. The combination of morphological operations is designed mostly based on Babu & Nallaperumal (2008) work. In first step, vertical edge detection is done which results in a binary image that contained vertical edges in white pixels while the remaining part of the image is black (Figure 5). Two columns with highest number of white pixels are then chosen and the distance between these columns is measured. Then the candidate region of interest is defined as the columns centered on these two columns and spanning 1/3 of the whole image. In next few steps, several operations are done to decrease the size of this candidate region in order to decrease the probability of existence of other yellow objects in this region.

**Morphological Operations**

Two morphological operations are applied in order to localize marker containing region more accurately. The equations of these morphological operations are given in (1) and (2) (Gonzalez et al 2009)

\[
\begin{align*}
Dilation & : A \oplus B = \left\{ z \left| (B)_{x} \cap A \neq \emptyset \right. \right\} \quad (1) \\
Erosion & : A \ominus B = \left\{ z \left| (B)_{x} \cap A^{c} \neq \emptyset \right. \right\} \quad (2)
\end{align*}
\]

In above equations B is the morphological element. Both horizontal and vertical dilation and erosion are done by changing B from horizontal line to vertical line. The result is shown in Figure 6.

Figure 5: Results of Vertical Edge Detection

Figure 6: Result of Morphological Operations

**Defining Search Space**

In next step the identified pixels with minimum and maximum index values in both x and y directions are chosen. The corners of a rectangle shaped region of interest are defined based on these pixels: \((x_{min}, y_{min} - 50), (x_{min}, y_{max} + 50), (x_{max}, y_{max} + 50), (x_{max}, y_{min} - 50)\). As it can be seen by adding 50 pixels to \(y_{max}\) and subtracting 50 pixels from \(y_{min}\) the rectangle which is defined based on outer corner pixels is extended in vertical direction. There are two reasons for this: Firstly, since the marker has a rectangular shape, the morphological dilation is more likely to extend the longer horizontal lines and the shorter vertical lines. Secondly, since the horizontal position of marker plays crucial role in measuring bearing, it would be inadvisable to overextend the horizontal search region and possible erroneously detect other objects. Results are shown in Figure 7. Although most of the time a small search space can be defined, when car is far from the camera and consequently marker is smaller, these steps may fail to find a search space. In these cases, the method chooses the whole image as the region of interest.
Finding Center of Mass

In last step of marker recognition, the determined region of interest is applied to yellow mask image in second step (Figure 4) and the center of mass of the yellow pixels is determined based on (3) and (4):

\[ m_{ij} = \sum_{x} \sum_{y} x^i y^j I(x, y) \]  
\[ \bar{x} = \frac{m_{10}}{m_{00}} \]  
\[ \bar{y} = \frac{m_{01}}{m_{00}} \]

Conversion from pixels to angles

To convert from pixel column to horizontal angle, multiple points with known coordinates in body frame of camera were chosen and the corresponding points in images were identified. The relationship between the bearing angle and the image coordinate is given by

\[ \tan \theta = \frac{d_2}{d_1} = \frac{d_3}{f} \]

and illustrated in Figure 9. Where \( f \) is the focal length, \( d_1 \) and \( d_2 \) are the coordinates of the feature and \( d_3 \) is the horizontal coordinate of the image point. By measuring \( d_2 \) and \( d_1 \), \( \theta \) can be computed and then by knowing the number of pixels from center of image to the target the ratio is computed. This is done for several images and the result shows that each pixel approximately represents an angle of 0.0891 degree.

DATA COLLECTION

In order to test the algorithm that is proposed above a two vehicle data set is collected on July 11, 2013 in open sky on a city street in Calgary. Each vehicle was equipped with a GPS antenna which was connected to a geodetic grade receiver. UWB radios were provided in order to measure direct ranges. For each vehicle tactical grade INS integrated system was used to obtain reference trajectory with cm level accuracy. Another GPS receiver is adopted in order to time tag the UWB ranges with GPS time. On a nearby building roof another geodetic grade receiver was used to obtain differential GPS reference trajectory. In
addition the lead vehicle was equipped with GoPro HD Hero camera.  

The reference trajectory was obtained for each vehicle using a commercial forwards/backwards carrier phase GPS/INS integrated solution. The IMU data is also used in order to determine the azimuth of camera equipped vehicle.

The UWB data needs to be synchronized to the GPS data. This was done by time tagging the UWB data with the clock of the system of the logging laptop which was itself been steered to match GPS time. The video data was synchronized by recording GPS time in an image frame at the start and end of the test.

The data rate for GPS measurements was 10 Hz and for IMU data 100 Hz. The data rate for UWB ranges measurements were approximately 5 Hz. The resolution of the camera was 1280 × 960 and the video data was recorded at 30 frames per second.

RESULTS

First, the accuracy of the obtained bearing measurement is shown. Then the relative navigation solution obtained using only the UWB ranges and vision derived bearings is presented. Finally, results obtained by integrating the range and bearing measurements with a vehicle-to-vehicle moving base station DGPS solution are shown.

Bearing Measurement Accuracy

The proposed image processing algorithm is applied to each frame of the video image, resulting in an independent bearing measurement of the center of mass of the target. The accuracy of these bearing can be evaluated by comparing them to the bearing obtained by the reference trajectory. The results are shown in Figure 12. The jumps in plot, particularly just after 120 seconds, are due to the fact that sometimes the method fails to determine correct region of interest. This occurs when objects with same color and shape enter the image, for example other yellow vehicles and road signs.

Relative Solution Results

Before integration it is worthwhile to see if the bearing and range measurements can lead to a reasonable relative solution. For this purpose, a local coordinate system is defined in the body frame the camera equipped vehicle. Figure 13 shows this coordinate system.

In order to determine the relative position the range measurements and bearing measurements are used. Figure 14 shows the range measurement error determined from the reference trajectories.
Figure 13: Local Coordinate System

Figure 14: Range Measurements Error

Integration with DGPS

An Extended Kalman Filter, discussed in Petovello et al (2012) work, was used to tightly integrate the DGPS, range and bearing data.

Four combinations of observations are tested: DGPS-only, DGPS + range, DGPS + bearing, and DGPS + bearing + range.

Figure 16 illustrates the trajectories, in terms of baseline components, for each solution. The reference trajectory is also plotted. Figure 16 shows that additional of the bearing measurement to the DGPS solution results in a slightly improved solution, particularly North direction. This is due to the fact that the vehicles are driving approximately East at this time, so the North component maps mainly into the across track direction, which is more strongly observed by the bearing measurement. In order to make it more clear, Along-Track and Across-Track errors are plotted in Figure 17. This shows that the addition of the bearing measurement significantly smooths the across track error, though a small bias remains. Adding UWB range measurement slightly improves the along track error as expected, except during the period from 80 to 100 seconds where the UWB range is biased.

In order to highlight the advantage of integration, Figure 15 and Figure 17 should be compared. In Figure 15, where solution does not benefit from integration with DGPS, the error in the bearing and range measurements significantly affect the results. However, due to the integration, and the use of a Kalman Filter, the integrated solutions are more accurate and more reliable.

Figure 18 shows the expected and real improvement obtained by adding bearing measurements. The expected results were obtained by computing a bearing using the reference trajectory, while the real results are obtained from the vision data. The real results are similar to the anticipated results.

Figure 19 shows the East, North and Up error for different solutions. The results clearly show improvement in the north/across track component due to adding the bearing measurement. The benefit of the UWB range is less clear in this case.
Figure 16: Trajectory for Different Solutions

Figure 17: Along/Across Track Error
Figure 18: Potential and Real Improvement Obtained by Adding Bearing Measurements

Figure 19: ENU Error
CONCLUSION AND FUTURE WORK

This paper investigated a combination of image processing algorithms to localize a target on a vehicle position in each frame in order to determine the bearing between two vehicles. These bearing measurements then integrated with UWB range and DGPS to provide an improved navigation solution. The results presented herein are proof-of-concept only and further investigation is required. Specifically, additional and longer data sets should be tested. Specifically scenarios with degraded GPS need to be evaluated to demonstrate the effectiveness of adding the range and bearing observations. The test presented in this paper involved an idealized marker on the target vehicle. For practical applications this will need to be replaced with a feature of the vehicle itself. Finally, both the marker or feature, and the search space can be tracked using Kalman Filter based image processing. This will be the next task in this ongoing project.

REFERENCES


http://www.vision.caltech.edu/bouguetj/calib_doc/, last update July 9, 2010
