Automated Drive West: What VSI Discovered from the 2,000+ Mile Drive Project with AV

by Jacob Miller and Sara Sargent · Technology Brief

Introduction

Last month, VSI Labs embarked on a 2,000+ mile cross-country road trip with one of our research vehicles. VSI's vehicle drove from Minneapolis, Minnesota to Santa Clara, California by applying AV applications on highways. The primary purpose of the Automated Drive West (ADW) project was to test the benefit of using precision lanes models and GNSS localization with real-time kinematic (RTK) corrections to improve the performance and safety of highway autonomous driving applications. Furthermore, we were seeking to better understand how these technologies operate across varying terrains, weather, and driving conditions throughout the project.

VSI's research vehicle used in this project is a 2018 Ford Fusion equipped with Dataspeed's by-wire control system. The two primary components used in this project are HERE high definition (HD) Live Map and an OxTS inertial navigation system (INS). The OxTS INS is compatible with RTK corrections enabling precision localization in the research vehicle. The vehicle was also equipped with a Delphi ESR radar, which was used for adaptive cruise control (ACC), a custom-built Linux-based computer running the lane keeping and ACC algorithms developed by VSI engineers, and a hotspot for internet access along the drive.

The ADW was the first experiment in which VSI attempted a cross-country highway drive in AV mode. Attempting a 2,000+ mile drive came with a number of development challenges. VSI engineers needed to develop new software and methodologies that allow us to test our AV system outside of a geofenced area. VSI also examined the performance of the HD map-based applications and the accuracy of INS/RTK-based localization through this project. This Tech Brief explains the preparation process of this project and our observations throughout the drive.

Preparation for ADW

VSI used two main AV applications for this drive: HD map-based lane keeping and lane changing and HD map-based ACC with radar. While VSI has done extensive research on lane keeping and ACC using HD maps, this research has always been conducted in a geofenced area. In previous tests, VSI engineers downloaded and processed the map data prior to testing. Because the ADW covered more than 2,000 miles of highway roads, it was necessary to develop a method of downloading and processing map data during the drive. In addition, VSI engineers had to adjust our AV system for map distortion.

DYNAMIC MAP DATA LOADING

Our dynamic map loading algorithm ran and repeated the following steps in order to download and process map data in real time during the drive.

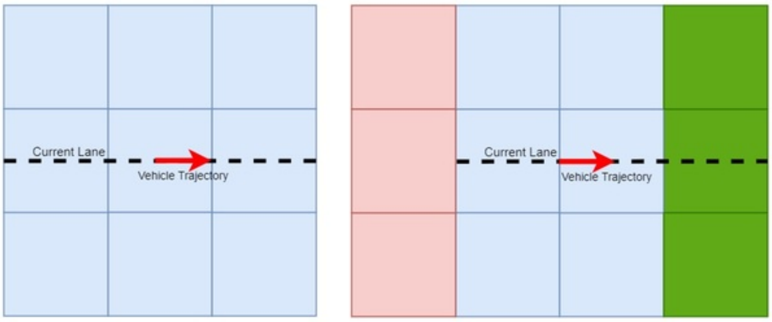
1. Download the surrounding map data
2. Process the surrounding map data
3. Seamlessly transition from the old map data to the new map data

The following sections describe details of these processes.

Downloading Map Data

The first challenge in the dynamic map loading process is downloading the correct map data given the vehicle's current location. VSI wrote a python script with ROS integration which receives the latest absolute localization information from the OxTS INS device. Using the current latitude and longitude, the relevant map data is determined and downloaded prior to triggering the next step in the dynamic map loading process.

HERE's HD maps are split into square tiles, 0.02197265625 degrees longitude/latitude in width, that are indexed according to their location on the map. The ID of a tile can therefore be calculated using a latitude and longitude pair that fall within the tile. Once the tile ID is found, the boundaries of the tile are calculated, which will be used to determine when the vehicle has entered a new tile. The script will continuously monitor the vehicle's location and download new map data each time the vehicle crosses a tile boundary. This process of downloading new map tiles is shown in the diagram below; as the vehicle crosses the eastern boundary of the center tile, the three tiles furthest to the west are discarded and the three tiles to the east of the new center tile are downloaded to be processed.



Dynamic Map Loading Diagram: blue tiles are tiles loaded in memory, green tiles are tiles being added into memory, red tiles are tiles being deleted from memory.

Since the vehicle could exit the current tile from any edge and at any angle, map data is loaded nine tiles at a time, as shown in the diagram above, giving the vehicle the center tile along with the eight surrounding tiles to drive in before new map data is necessary. To find the eight surrounding tile IDs, VSI simply offsets the current latitude and longitude values by the width of the tiles in each direction and uses the same method to calculate the tile ID from the adjusted latitude and longitude.

Now that all relevant map tiles have been determined, the script can download the data for each tile from HERE's database. The script first checks if the downloaded file already exists, and only downloads the tile if it has not already been downloaded. This can significantly cut down on the time spent processing the map data, especially if the map data for the designated route has been downloaded ahead of time. Once all the data is downloaded, the scripts publishes the HERE tile IDs and the file names corresponding to newly added tiles to be processed, triggering the next step in the process.

Processing Map Data

The processing of the map data is encapsulated in a C++ class, with Json pointers to the map data and functions for parsing the protobuf files into a Json format. The primary function for processing new data is triggered by the script that downloads the map data, processing only the newly added files sent in the ROS message.

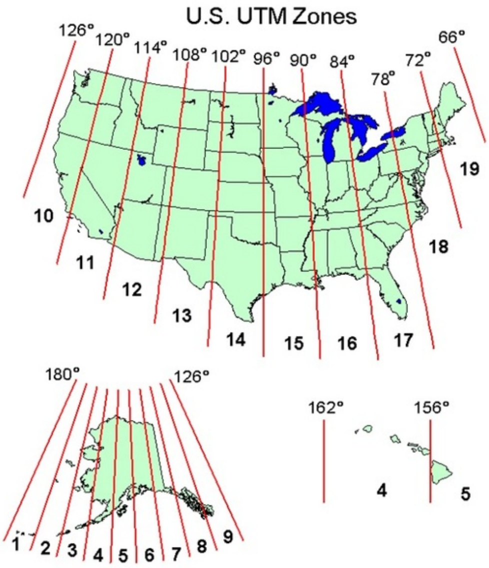
The protobuf data is converted into a temporary Json object that is optimized for later processing of the map data to find and follow the current lane. The Json object stores data into two main categories: lane groups and lane group connectors. Each lane group contains a HERE tile ID, lane group ID, two lane group connector IDs, lane group coordinates, and a set of lanes within that lane group. Each lane contains a lane ID, two lane connector IDs, a direction of travel, and a set of lane coordinates, which can be used for lane keeping. Each lane group connector contains the set of lane groups that are linked by that connector, which is a critical piece of information when following the current lane over long distances.

Since some of the nine tiles may already be stored in the current map data Json object, the lane groups with tile IDs that match the tile IDs sent from the script are added into the temporary Json object. Once all of the relevant lane groups have been added, the temporary Json object overwrites the current map data stored in the class.

After all the new map data is downloaded and processed, the map data pointer in the control stack is updated, with a lock around this critical section to assure that no race conditions occur. A new target path is found using the new map data, and the steering command slowly transitions from the current target path to the new target path. Although not strictly necessary, the slow transition to the new target path gives the driver enough time to react in case any errors occurred in the loading of the new map resulting in a corrupt target path.

MAP DISTORTION AND THE UTM COORDINATE SYSTEM

One of the major difficulties with using maps over large distances is dealing with map distortion. While distortion is negligible over a small geofenced area of a map, the distortion can seriously disrupt map-based lane keeping when relying on centimeter-level accuracy of the map. VSI opted to use the Universal Transverse Mercator (UTM) coordinate system for the Automated Drive West to solve the distortion issues.



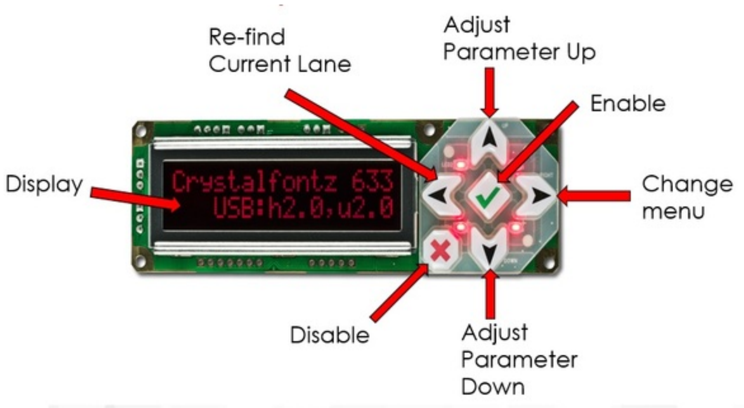
UTM Coordinate System (Image Source: XMS Wiki)

A significant challenge to using the UTM coordinate system is maintaining smooth control when transitioning between zones without disengaging. The UTM coordinates wrap around from the minimum easting value to the maximum easting value when crossing the western zone boundary. Due to this characteristic of the UTM coordinate system, a method is needed to immediately and simultaneously switch the map data and the vehicle's position into the new UTM zone when crossing the boundary.

To accomplish this, some processing must occur prior to reaching the zone boundary. When the vehicle is within two HERE tile widths of a UTM boundary, any new map data that is being processed will be converted into UTM coordinates for both the current UTM zone and the adjacent UTM zone. As soon as the vehicle crosses the UTM zone boundary, the map data will be overwritten by that of the new UTM zone, the target path will be found in the new map data, the vehicle's location will be converted into UTM coordinates of both the new UTM zone and the previous UTM zone, and a separate orientation offset will be calculated for each location. The steering command will be calculated as a linear combination of the trajectory error between the previous zone's target path with the previous zone's location and orientation, and the trajectory error between the new zone's target path with the new zone's location and orientation. Similarly to the method described earlier in this report when transitioning between HERE tiles, it is not strictly necessary to slowly adjust the steering command from the old zone to the new zone, but it gives the driver ample time to disengage and take control of the vehicle if something were to malfunction.

INSTALLATION OF HUMAN MACHINE INTERFACE

To prepare for this drive, VSI also developed a new human-machine interface (HMI) device that communicates with the vehicle's domain controller. The device was set up to not only display different outputs regarding the vehicles control commands such as the steering angle and target speed, but also receive certain input from the driver.



VSI Labs HMI device installed in the research vehicle

The HMI device gave the driver the ability to instantly adjust parameters such as the maximum speed for ACC or and center offset for the vehicle's orientation during the ADW, providing a comfortable and smooth ride without unnecessary disengagements. Since the HMI device is configurable to our needs at the time, it rapidly sped up the debugging and testing process for ADAS functionalities such as lane keeping and ACC while preparing for this project.

Key Findings

Overall, our HD-map based lane keeping and ACC worked well throughout the drive. We observed that the HD-map based system performed adequately even when lane markings on the highways were not good for much of the drive, making a vision-based system unfeasible as an independent system.

We did not enable the system due to dangerous road conditions or conditions where the safety driver would not have adequate time to react. Such conditions include winding roads, low visibility, high roadways without guardrails, areas with pedestrian traffic, and late-night driving. Also, the system was disengaged in areas such as highway exits, construction zones, newly constructed roadways, areas with lack of connectivity and RTK base stations, areas surrounded by dense forest, and when the vehicle was driving near large vehicles.

While many of the observations along the drive were expected due to limitations of the system, key findings from this project are as follows:

- The vehicle had one or both autonomous systems (ACC and lane keeping) enabled for 1,767 miles during the drive.
- Even without RTK corrections due to lack of connectivity or too great of a distance to a base station, the OxTS INS was often able to maintain an accuracy with under 30 cm of uncertainty, which was enough to stay centered in the lane on straight highways.
- On smaller highways where the map data was not expected to be accurate enough to enable, VSI was sometimes able to engage radar and map-based ACC but not lane keeping. For ACC, the lanes only need to be accurate enough to filter our extraneous radar points rather than the centimeter-level accuracy necessary for lane keeping.
- When driving near semi-trucks, human drivers naturally keep to the far side of the lane to give the truck more room and avoid the pull from the truck. Our map-based lane keeping system did not take this tendency into account, making passing semi-trucks more anxious for the safety driver and passengers.
- The best performance from the autonomous system took place on Interstate 90 in South Dakota and Interstate 80 in Utah and Nevada. This is where the map data was accurate for the longest periods of time, often times allowing the system to stay enabled for over 50 miles at a time.
- The radar in the front of the vehicle accumulated many bugs and dust along the drive. The output from the radar was unaffected, but other external sensors such as camera and LiDAR might see greater affects from this. Sensor cleaning will be necessarily for autonomous vehicles driving long distances.
- Even with a fan cooling system installed in the trunk, the temperature of the trunk would occasionally exceed 100°F. When the trunk temperature exceeded 100°F, the team in the car would first turn the A/C to maximum in the cabin to push cool air to the trunk. If the temperature still would not lower, the team would pull over and let the trunk air out so that the electronics in the trunk would not overheat. Significant cooling mechanisms will be needed to keep electronics cool for autonomous vehicles that drive for long periods of time.

Lastly, throughout this drive, we reaffirmed the importance of safety driving when testing autonomous vehicle technologies on public roads. The safety driver needs to be alert at all times and be educated on how to use the system, where the system will perform well, and most importantly when the system might fail. Safety driving is much more mentally taxing than regular driving. The safety driver does not know what the inputs are and must constantly anticipate what might happen next. During this trip, it was important to take breaks from driving every few hours, even just to stop at a gas station.

For our regular testing, we normally have two people in the car: one safety driver and one engineer. However, for this trip, there were three people in the car to ensure safe testing including the safety driver, the engineer, and the third monitor who sat in the passenger seat and managed the HMI controller to set and adjust desired speeds, adjust lane position around large vehicles, and monitor the temperature of the trunk.

There was a lot of communication required between the safety driver and the engineer. The engineer was watching the lane model to make sure it aligns with what the driver was seeing on the roadway, monitoring the level of position accuracy from the INS device, the radar readings to see whether the radar was identifying the closest in-path vehicle for ACC, and finally making sure that the maps were downloading quickly enough. The driver communicated when things became uncomfortable and needed to judge when to ask for the status of certain systems so that the engineer could assist in determining whether to engage, stay engaged, or disengage.

Conclusions

After more than 2,000 miles of exploring the capabilities of lane keeping and ACC with precision lane models and INS localization with RTK corrections, VSI gained valuable insight and data to improve the safety of these systems. Testing these map-based solutions in isolation showed the strengths and weaknesses of the system, which is the vital first step in developing redundant systems to increase the safety of autonomous systems. The Automated Drive West provided much needed variety in the road conditions and situations experienced by the VSI research vehicle, giving insight that would not be possible to obtain when driving in a geofenced area with known conditions.

VSI will provide more details on the development process and results of the ADW project in an upcoming Pro report.

This document was created on 09/26/2019 at 10:08:34AM CST

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