White Paper

Submitted to Indy AV Challenge

University of Florida and Kookmin University

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1. The Team and Its Members

Researchers at the University of Florida (UF), Gainesville, FL and Kookmin University (KU), Seoul, South Korea are teaming together to enter the Indy Autonomous Vehicle (AV) Challenge. Both schools have a long history of autonomous vehicle development and a twenty-year history of collaboration with each other.

The UF team is headed by Dr. Carl D. Crane who has over thirty years of experience in the area of autonomous ground vehicle development. He has been Principal Investigator on several autonomous vehicle development projects for the Air Force Office of Scientific Research (AFOSR) and the Department of Energy (DOE). He also was the project lead for UF's entry into both DARPA Grand Challenge competitions (2004 & 2005) and the DARPA Urban Challenge competition (2007).

The KU team is headed by Dr. Jungha Kim who has over twenty-five years of experience in this research area. He is a Professor of Mechanical Automotive Engineering and has served as the head of the College of Automotive Engineering at KU. His research team has developed many autonomous vehicles and participated in numerous development competitions.

2. The Team's History with Automation

University of Florida

The University of Florida has over thirty years of experience in developing autonomous ground vehicles. Figures 1 and 2 show heavy construction equipment that was automated in the 1990's for operations by the U.S. Air Force. The application was for runway repair and obstacle clearance. Figure 3 shows a convoy operation, where the lead vehicle is human driven and the follower vehicle is autonomous. What was unique about this application was that no GPS was used on either vehicle and no radio communication occurred between the vehicles. Figure 4 shows a vehicle that was automated to perform range clearance operations for the Air Force. The surface is first cleared, then magnetometer data is collected to locate underground ordnance. Lastly a backhoe type vehicle is used to dig up the underground ordnance.

Fig. 1: Auton. Excavator

Fig. 2: Auton. Dozer

Fig. 3: Autonomous Convoy Operations

Fig. 4: Autonomous Range Clearance

In the 2000's, the University of Florida competed in both DARPA Grand Challenges and the DARPA Urban Challenge. Figures 5 and 6 show the vehicles that were developed for the 1st and 2nd Grand Challenges and Figure 7 shows the vehicle developed for the Urban Challenge. One main contribution of the UF team was the development of the concept of smart sensors. Individual sensors would generate a two-dimensional grid-based traversability map. This allowed for simple merging of data into a final world model through which a motion path could be generated. A second contribution was the development of the Adaptive Planning Framework whose purpose is to identify the 'best appropriate' behavior for the autonomously navigating vehicle. The DARPA Urban Challenge was broken down into six primary vehicle behaviors, i.e. lane navigation, change lanes, U-turn, intersection, open-area, and parking. The Adaptive Planning Framework incorporated processes called Situation Assessment Specialists which would use sensed data to make findings. An example

Fig 5: Grand Challenge, 2004

Fig 6: Grand Challenge, 2005

Fig 7: Urban Challenge, 2007

would be to determine if the travel lane is clear for the next 25 meters. Another example would be to determine if it is appropriate to change lanes at that instant (no oncoming traffic, not near an intersection, good line of sight). Next, six Behavior Specialists, one for each of the six behavior categories, would evaluate whether their assigned behavior was appropriate at that instant. A final component, named the Decision Broker, would ultimately decide which behavior to execute based on the recommendations from the Behavior Specialists. The system performed very well during the DARPA Urban Challenge and was utilized in other sponsored research projects.

UF has also competed in three additional competitions. Figure 8 shows the SubjuGator which competed in the 2019 RoboSub competition. UF has competed annually in this event starting in 1998 and has placed in the top 3 seven times, including first place in 2005, 2006, and 2007. Figure 9 shows the 2017 PropaGator autonomous surface vehicle which competed in the AUVSI RoboBoat competition. UF placed first in the 2013 competition. Figure 10 shows the 2018 NaviGator Autonomous Maritime System (AMS) vehicle which competed in the bi-annual AUVSI Maritime RobotX competition. UF participated in the 2016 and 2018 competitions and finished 1st and 4th respectively.

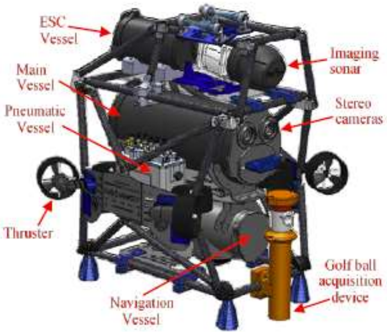

Fig 8: UF SubjuGator

Fig 9: UF PropaGator

Fig 10: UF NaviGator AMS

Kookmin University

Kookmin University's unmanned vehicle Laboratory (KUL) was established in 1997. Initially, technology was developed by installing unmanned technologies on various platforms such as ATVs and carts. Since then, KUL has built self-driving cars and developed self-driving systems based on commercial vehicles. Figure 11 shows the Kookmin research team along with some of their developed autonomous vehicles.

Fig 11: Kookmin University's Unmanned Vehicle Laboratory

The KUL developed self-driving technology can be categorized as SAE Level 3, i.e. sustained autonomous driving is performed with the expectation that the human driver will be ready to respond to a request to intervene when issued by the autonomous system. The ability to generate and execute a motion path is performed after recognition and judgment based on various sensor information, such as Lidar, Camera, and GPS. Vehicles can perform functions such as Auto Valet Parking, Lane Keeping, Lane Change, Smart Cruise Control, and Driving Lane Keeping. Figure 12 shows the KUL developed vehicles along with images that show the autonomous functions.

KUL has also won awards in 2010 and 2014 at Hyundai Motor Company's self-driving car competition (ranked 3rd and 2nd respectively). KUL has also developed its own self-driving platform called 'TRAM' which carried out shuttle driving at Kookmin University (see Figure 13). Currently, KUL is developing deep learning-based algorithms for sensor fusion and map construction using lidar and camera input (see Figure 14).

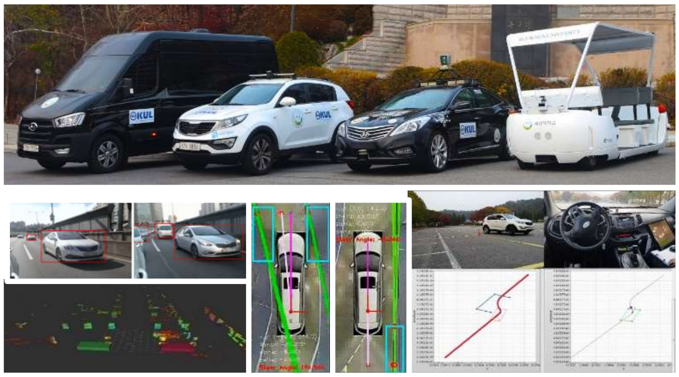

Fig 12: KUL Developed Vehicles and Display of Auto Valet Parking, Parking Space Detection, Lane Keeping, Lane Change, Blind Spot Detection Functions.

Fig 13: TRAM

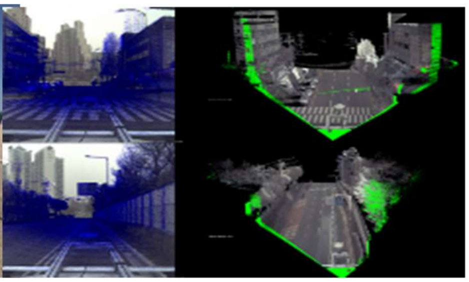

Fig 14: Sensor Calibration / Map Matching

3. Plans for Competing in the Competition

a. UF/Kookmin Development Plan

One scheduling concern is that the Indy Light vehicle will not be available to the teams until May 2021 while the race is only five months after that in October 2021. It is true that well designed and tested software could be smoothly transitioned from the dynamic simulator to the vehicle. However, the team believes that it can create a more robust system if software and hardware can be tested together earlier in the competition.

To address this, the team has obtained permission from New Smyrna Speedway to test at their track. This speedway is 110 miles from the UF campus. It is a half-mile asphalt track with 23° banking in the turns (see Figure 15). Average lap speeds of 75 mph are possible. In January, the UF-KU team travelled to the speedway and logged lidar, camera, and GPS/IMU data to be used for SLAM testing. The point cloud with 1.8 million data points is shown in Figure 16.

For a test vehicle, UF has purchased a Tony kart go-kart specifically for this project. This kart is capable of speeds up to 80 mph. Students are designing and implementing actuators with a Velodyne Puck, cameras, and a Sylphase GPS/IMU. The UF kart is shown in Figure 17. The schedule goal is to have the UF kart driving autonomously at New Smyrna Speedway in time to be shown in the Round 2 video that is due by 20 May 2020.

In parallel with this, KU is automating one of their university team's Formula SAE vehicles (see Figure 18). The schedule is for them to ship the vehicle to UF by Feb 2021 so that two autonomous cars can be tested simultaneously at New Smyrna Speedway. Two cars will allow for testing of the higher-level functions associated with vehicle passing.

Fig 15: New Smyrna Speedway

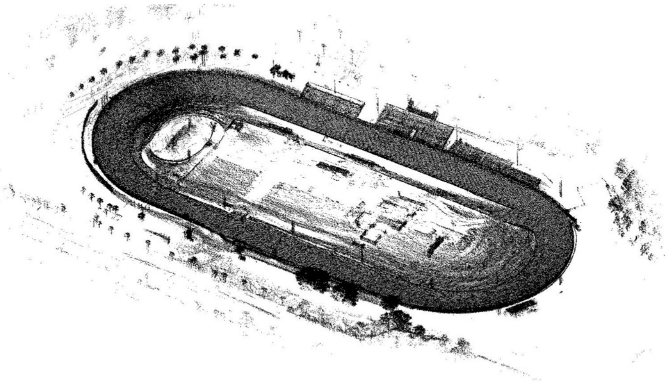

Fig 16: Point Cloud Model of New Smyrna Speedway

Fig 17: UF Tony Kart

Fig 18: KU Formula SAE Vehicle

b. Approach to Automated Vehicle Software Architecture

The approach to the software architecture will be modeled on the Adaptive Planning Framework that was developed by UF for the DARPA Urban Challenge. As previously mentioned, the architecture consists of multiple software modules named Situation Assessment Specialists which make findings based on sensor inputs and Behavior Specialists which evaluate possible vehicle behaviors.

For this competition examples of Situation Assessment Specialists would be specialists that determine if the track in front of the vehicle is clear for the next 75 m, if there is any vehicle within 25 m behind which is gaining on us, or if a potential passing lane is free of occupancy. Other specialists would monitor if a caution command, red flag command, or heartbeat signal was received.

A set of possible behaviors for the vehicle will be defined and one Behavior Specialist module will correspond to each of these behaviors. The Behavior Specialists calculate a score as to whether it is believed that their behavior is appropriate at this time. Examples of behaviors are ‘drive racing line’, ‘follow car’, ‘pass left’, ‘pass right’, ‘caution’, and ‘red flag’. For this competition, heuristics, based on testing, will be used to develop the behavior scoring algorithms. Next, the Behavior Arbiter module selects the ‘best’ appropriate behavior and acts to implement it.

Figure 19 shows the planned architecture as it will be implemented on the UF kart for the case where the kart is qualifying, i.e. the kart is the only vehicle on the track. Localization is accomplished based on comparison of sensed data to the track data (the point cloud in Figure 16) as seeded by GPS/IMU data. A Local World Model is created around the vehicle position to plot the location of static and moving objects. Situation Assessment Specialists make their findings based on the local world model and any other available inputs. The Behavior Specialists score their corresponding behavior based on the findings and the Behavior Arbiter selects the ‘best’ appropriate behavior.

The output of all behaviors will be the same, i.e. a list of goal positions and orientations with speed. Initially a simple pure pursuit method will be used to follow the trajectories, but this will be augmented based on results of simulation and hardware testing.

For the racing scenario, additional Situation Assessment Specialists and Behavior Specialists will have to be developed along with additions to the Local World Model. For the Local World Model, it will be necessary to estimate model states at future times based on the current and anticipated velocity states of all vehicles. Situation Assessment Specialists which monitor if we are about to be overtaken or if it is safe and appropriate to move laterally on the course will be implemented. Behavior Specialists which evaluate whether a ‘passing behavior’ or ‘are being overtaken’ behavior is appropriate will be added.

The UF/KU team has confidence in implementing this architecture in this application. The challenge here is whether behavior decisions can be determined fast enough considering the high speed of the vehicle. Previously, modules used the Joint Architecture for Unmanned Systems (JAUS) protocol to communicate with each other and the system was able to operate at approximately 30 Hz. Here, the Robot Operating System (ROS) will be used and the operating rate will be determined.

c. Simultaneous Localization and Mapping (SLAM)

SLAM was not used by UF during the DARPA Grand and Urban Challenges. Rather, maps were built using GPS and IMU data to register all objects in a global coordinate system. The problem with this is that the GPS error is not known at the map creation time. When driving through the map, a different GPS error would exist so things ‘might not quite line up’. Added onto this was that multi-beam lidar units were very

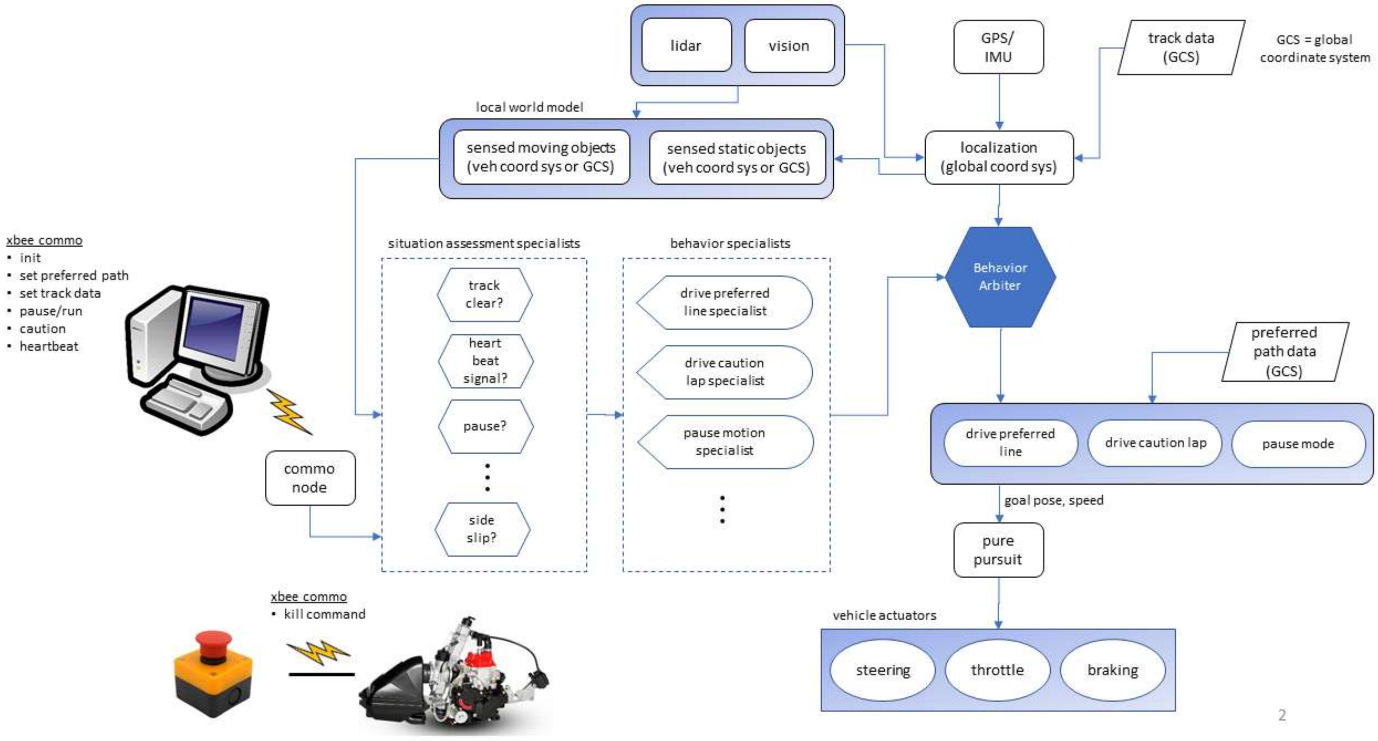

Fig 19: Adaptive Planning Framework Architecture for UF Kart

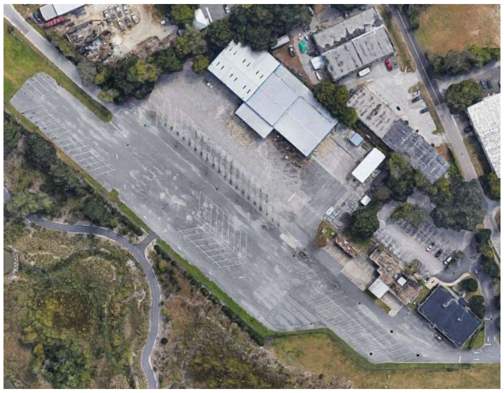

Fig 20: Gainesville, FL Test Area

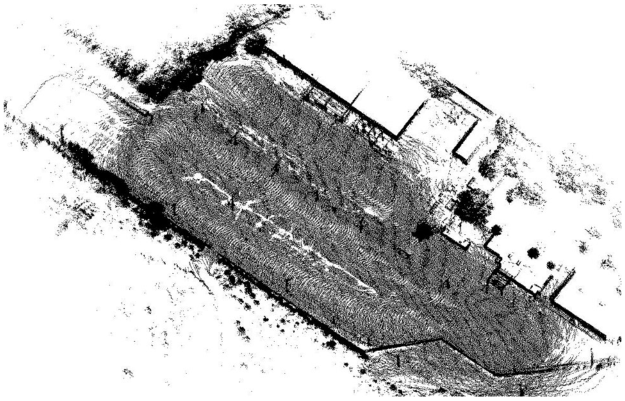

Fig 21: Point Cloud Model of Gainesville, FL Test Area

expensive so many of the measurements were taken by single beam units.

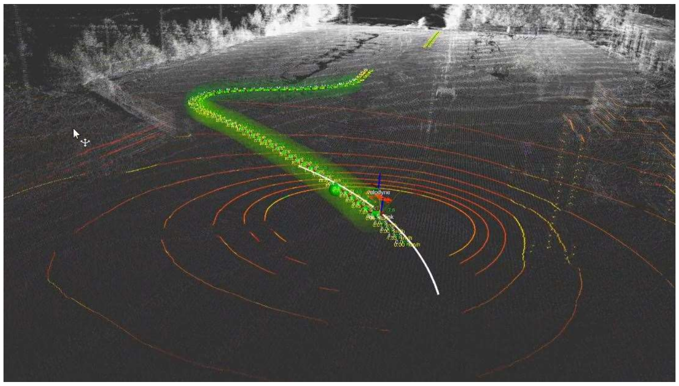

Fig 22: Navigation Path ; a priori point cloud (white) ; current sensor data (red, yellow) ; path (green)

Today, the UF vehicle uses a SLAM approach to localize itself in its environment. Figure 20 shows a test area in Gainesville, Florida. A point cloud map, shown in Figure 21, was generated using a SLAM technique based on lidar data collected by driving through the area. None of the data points are registered to an absolute global coordinate system. In other words, GPS was not used to determine an absolute latitude and longitude for the vehicle position as it collected the data. Rather, an origin was established based on where the first data was collected.

Figure 22 shows a route (green color) that has been planned through the test area. The a priori map data points are shown in white. The instantaneously collected lidar data is shown in red and yellow. The position and orientation of the vehicle has been successfully determined based on matching the instantaneous points to the points in the map. No GPS was used in this example, but GPS could be used to provide a seed location from which to start the point matching process.

The SLAM approach has been successfully implemented on the UF Urban Challenge vehicle. Data has been collected at New Smyrna Speedway (Figure 16) so that it may be tested and further developed for higher speeds. Different point matching algorithms must be investigated to determine what technique will work well in the high-speed environment of this competition.

d. Testing

The UF/KU team has placed a large emphasis on hardware testing. As previously mentioned, the New Smyrna Speedway has agreed to allow for extensive testing. Although this is only a half mile track, which will limit speeds, it will allow for the

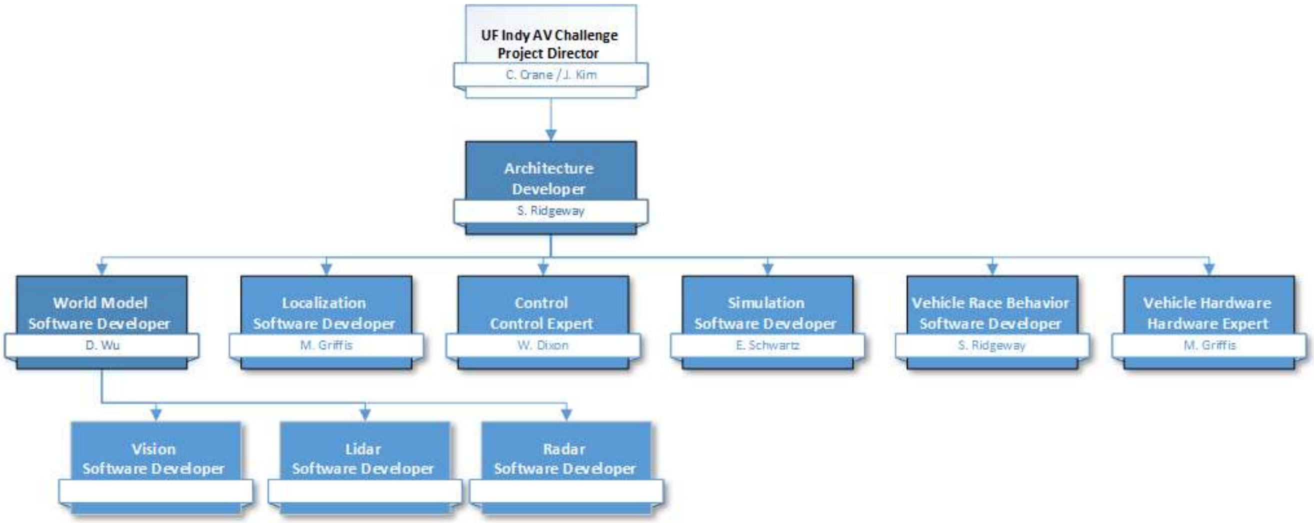

Fig 23: Organization Chart with Faculty Listed

testing of software and hardware protocols and the implementation of vehicle behaviors. The UF/KU team is building two autonomous vehicles to test on this track. The Indy Light vehicle will also be tested at the New Smyrna Speedway between the times of track access at the Indianapolis Motor Speedway.

e. Other Technical Specifications and Insights

Two topics deserve comment. The first has to do with communication with the vehicle related to safety at IMS. Communication with the vehicle is important for safety reasons. Vehicles may need to be commanded to switch to a caution behavior or a red flag condition may be needed. Maintaining communications over the large area of IMS is important and it must be coordinated with all the vehicles at the track.

A second topic has to do with the exact implementation of how to 'kill' or immediately stop a vehicle. The on-board computer may have crashed so the nominal communication channel may be down. For the UF kart and KU vehicles, parallel communication channels can be run from which the engine of the vehicle can be turned off. Mechanical means that are independent from the standard braking method can be implemented to apply the brakes. For example, a pressurized air cylinder can be used to engage an actuator to press on the brake master cylinder. The valve on the air cylinder is opened if the 'kill' command is received.

Many other details can be addressed during the team meetings with Clemson University. Details with regards to what sensors and computer resources should be used can be discussed then.

f. Approach to Project Management and Fundraising

The team organization is shown in Figure 23. Dr. Crane and Dr. Kim will head the UF and KU efforts. Responsibilities are divided between faculty and their students as shown in the figure. The important technical areas are sensing and modeling, localization, control, simulation, race behavior, and hardware.

Presently, faculty and students are volunteering time to the project except for the six undergraduate students who are automating the UF kart. These students are receiving course credit for the Mechanical and Aerospace Engineering Department's capstone design course.

UF has committed approximately \$60K to pay for the kart development and for travel to New Smyrna Speedway and IMS. Similarly, KU is working to obtain approximately \$80K from their government to pay for the development of their automated Formula SAE vehicle and for transport and travel costs. The UF Development Office will be leveraged to find additional corporate and private donors for the project.

4. Summary and Conclusion

The UF/KU team is fully committed to this project. A local test area has been identified. The local test vehicle, computers, and sensors have been purchased. A development plan has been created whereby two vehicles will be able to 'race', although at slower speed than at IMS.

In summary, the team greatly appreciates this opportunity to compete at IMS. The experience you are offering our students is outstanding.