A NAVIGATION SUBSYSTEM FOR AN AUTONOMOUS ROBOT LAWN MOWER

by

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Submitted in partial fulfillment of the requirements for the degree of Master of Science

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(signed)____Roger Quinn____________________________________

(Chair of the Committee)

____Francis Merat__________________________________________

____Marc Buchner__________________________________________

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(Date) __06-29-2011__________________
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<tr>
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<th>Full Form</th>
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<tr>
<td>ANB</td>
<td>Athena Navigation Board</td>
</tr>
<tr>
<td>ANS</td>
<td>Athena Navigation System</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CEP</td>
<td>Circular Error Probable</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off The Shelf</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DGPS/DGNSS</td>
<td>Differential GPS/Differential GNSS</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>ENU</td>
<td>East, North, Up</td>
</tr>
<tr>
<td>EVS</td>
<td>Embedded Vision System</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>GCC</td>
<td>GNU Compiler Collection</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite Systems</td>
</tr>
<tr>
<td>GNU</td>
<td>GNU’s Not Unix</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IGVC</td>
<td>Intelligent Ground Vehicle Competition</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>ION</td>
<td>Institute of Navigation</td>
</tr>
<tr>
<td>KF</td>
<td>Kalman Filter</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
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<tr>
<td>NI</td>
<td>National Instruments</td>
</tr>
<tr>
<td>NMEA</td>
<td>National Marine Electronics Association</td>
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PAC – Programmable Automation Controller
PPS – Precise Positioning Service
RF – Radio Frequency
RIO – Reconfigurable Input/Output
RMS – Root Mean Square
RT – Real Time
RTK – Real Time Kinematic
SA – Selective Availability
SBAS – Satellite Based Augmentation System
sbRIO – Single Board RIO
SPS – Standard Positioning Service
TOA – Time of Arrival
TTFF – Time To First Fix
WAAS – Wide Area Augmentation System
A Navigation Subsystem for an Autonomous Robot Lawn Mower

Abstract

by

BRADLEY EVAN HUGHES

This thesis describes a cost effective, accurate, and precise electronic navigation system which is suitable for outdoor commercial mobile robots. The hardware design of the system incorporates commercial off the shelf Global Positioning System receiver modules and support electronics. The software design of the system makes use of an open source positioning library to enable Real Time Kinematic satellite positioning. The designed navigation system has been integrated with a preexisting mobile robot platform, an autonomous robot lawn mower, which includes a set of reference sensors to provide accurate robot pose information. The reference platform is used to quantitatively evaluate the performance of the new cost effective system. A degradation factor of 1.7 in terms of positional accuracy is traded off in favor of achieving a cost savings factor of about thirty.
CHAPTER 1: INTRODUCTION

The CWRU Cutter robots, designed and built at Case Western Reserve University in Cleveland, Ohio, are a series of autonomous intelligent ground vehicles built to compete in the Institute of Navigation’s Annual Robot Lawn Mower Competition. The first three versions of CWRU Cutter tested the feasibility of autonomously mowing grass using commercially available sensors and computational platforms. CWRU Cutter IV is the first robot developed that includes custom-built electronics to enable cost-effective production.

Team CWRU Cut, pronounced “crew cut,” is an ensemble of undergraduate and graduate students that perform research in autonomous mobile robotics at Case Western Reserve University. The team is sponsored by MTD Products, Incorporated, a Valley City, Ohio company. MTD Products produces a variety of consumer products intended for lawn and garden care.

For the past four years, the team has been developing a mobile robotics platform. In 2008, CWRU Cutter placed 3rd at the 5th Annual ION Robotic Lawn Mower Competition. In 2009, CWRU Cutter 2.0 placed 1st at the subsequent 6th Annual ION Robotic Lawn Mower Competition. In 2010, CWRU Cutter C placed 1st at the 7th Annual ION Robotic Lawn Mower Competition. Most recently, CWRU Cutter IV placed 1st at the 8th Annual ION Robotic Lawn Mower Competition. In addition to competition success, the team members have yielded several scholarly publications and theses: (1) (2) (3) (4) (5) (6).
CWRU Cutter IV, pronounced “crew cutter ivy,” is the most recent addition to the CWRU Cutter family of autonomous intelligent ground vehicles. CWRU Cutter IV focuses on minimization of cost by migrating core computational components to custom-built electronics.

In order for an autonomous robot lawn mower to be a viable consumer product, the cost of the prototype system must be reduced by roughly fifty times. One major component in the CWRU Cutter’s cost is the navigation subsystem. The goal of this thesis is to develop a navigation subsystem that can cut the cost of the navigation components by a factor of thirty.

The prototype custom navigation system includes both hardware and software components. The hardware includes COTS cost-effective sensors and COTS support electronics to perform data acquisition. The software developed for both the embedded electronics and high-level controller include real-time sensor acquisition drivers and high-level analysis tools. The high-level analysis tools are capable of comparing navigation solution uncertainties between sensor suites. The robot’s onboard ground truth sensor system is used to measure quantitative performance. The use of these tools together can be used to determine suitable navigation components for a commercially-viable consumer autonomous robotic lawn mower.

Chapter 2 discusses the background of navigation technologies. Chapter 3 outlines the CWRU Cutter mobile robotics architecture. Chapter 4 presents the detailed design of the CWRU Cutter architecture’s positioning software. Chapter 5 presents results of the low-
cost hardware platform as integrated in the CWRU Cutter robotics platform. Chapter 6 outlines conclusions and future work.
CHAPTER 2: BACKGROUND

Satellite Navigation Technologies

GPS

Functional GNSS systems have been in functional testing since the early 1960s. One of the earliest two-dimensional positioning systems was TRANSIT, sometimes referred to as NAVSAT (Navy Navigation Satellite System). Development of the TRANSIT system started a few days after the launch of the Soviet Sputnik I satellite by Russia. Two scientists at the Applied Physics Laboratory of Johns Hopkins University, George Weiffenbach and William Guier, were able to determine Sputnik’s precise orbit by analyzing the Doppler shift of RF signals transmitted from Sputnik during a single pass (7). In 1958, the development of TRANSIT was started; it culminated in a failed launch of the Transit 1A satellite vehicle in 1959. A successful launch, roughly one year later, yielded a working satellite navigation system adopted by the Navy in 1964. The system was retired in 1996 after GPS was a fully vetted and operational replacement to TRANSIT.

The GPS program, referred to as Navstar, entered Phase I concept validation between 1973 and 1979. GPS integrated research from the United States Air Force’s 621B three-dimensional positioning system with lessons learned from the TRANSIT program. NTS-2, the second “Navigation Technology Satellite,” was launched in June 1977 and transmitted the first GPS format signals from space. The satellite malfunctioned after roughly eight months. After the successful launch of twenty-four Block I and Block
II/IIA satellites, the GPS constellation entered “full operational capacity” on April 27th, 1995 (8). A more in-depth timeline of the development of GPS and a table of specific events is available in (9).

A minimum constellation of twenty-four satellites guarantees that a sufficient number of satellites are in view at every point on Earth in order to achieve an accurate position fix. A minimum of four satellites are required to compute position (and measure time) in all three Cartesian axes. This is achieved through the use of pseudoranges – the measured effective distance to each satellite. The pseudorange is calculated from the TOA of the RF signal containing the GPS navigation message. If more than four pseudoranges are available, multilateration is used in order to provide a more accurate solution of position and time.

Initially, the GPS added noise to the transmission of the navigation message in order to reduce the accuracy of the SPS while providing a predictable position accuracy of 100 meters horizontally and 156 meters vertically. The goal was to reduce the probability that an enemy of the state would use GPS for military operations against the United States of America. The PPS was provided to military receivers that make use of the encrypted P(Y) code. This additional timing information can be used to resolve to 22 meters horizontally and 27.7 meters vertically. In 2000, SA was discontinued at the direction of the President of the United States in order to provide a more accurate positioning service. At the time of deactivation, CEP of dual-frequency positioning
solutions at the Colorado Springs, Colorado observation station decreased from 4.6 meters to 2.8 meters (10).

The innovation of better oscillators, antennas, and signal processing techniques can commonly provide meter accuracy with a single-frequency GPS receiver. Dual-frequency GPS receivers can generally obtain sub-meter accuracy while providing better day-to-day precision as a result of local ionospheric modeling. The incorporation of pseudoranges from GLONASS and Galileo satellites, as outlined in the next section, can reduce solution errors by providing more terms in the multilateration step. SBAS, DGPS, and RTK positioning techniques are used to further improve solution quality by correcting for clock errors in the satellite network, ephemeris errors, or wide area ionospheric errors.

**GLONASS**

GLONASS is a GNSS system developed by the Russian Space Forces with the first satellite launched in 1982. GLONASS uses a different frequency band and modulation technique for digital communication compared to the GPS constellation. However, newer GLONASS satellites transmit not only GLONASS L1 FDMA signals, but also transmit GPS L1 CDMA signals in order to allow for integration of GLONASS RF signals with current software-defined GPS receivers (11).
Galileo

Galileo is the European Union and European Space Agency’s satellite navigation system that has been under development since the early 2000s and is not currently operational. It is predicted that the system will be operational by 2018 (12).

SBAS

Satellite based augmentation systems are comprised of ground-based facilities that monitor the health and precise ephemeris of the GPS satellite constellation. This information is sent via RF uplink to a satellite which transmits corrections to end user GPS receivers. The SBAS message usually contains corrections to the ephemeris, atmospheric model parameters, or ionospheric model parameters. Some of these services are subscription-based, such as the Omnistar Worldwide DGPS service. Omnistar provides a variety of products with varying accuracy from sub-meter to sub-decimeter (13). WAAS is a SBAS provided for free by the FAA in order to provide end users with corrections that make GPS reliable and accurate enough for use in aviation. The application of the WAAS navigation message “improves GPS signal accuracy from 100 meters to approximately 7 meters” (14).

DGPS/DGNSS

DGPS or more broadly, DGNSS, is a technique that makes use of a local static base station in order to measure variations in satellite pseudoranges. These pseudorange residuals are transmitted from the base station to the rover via a low-bandwidth radio link. These residuals are applied to the measured pseudoranges on the rover. This type
of correction dramatically reduces long-term temporal effects and stratospheric effects that are slower than a few minutes in dynamics.

**RTK**

Real Time Kinematic GPS is a method that utilizes measurement of the RF carrier phase of the GPS navigation message. This phase measurement can be used to resolve satellite position to within roughly 20 centimeters whereas the navigation message provides roughly 3-5 meter pseudorange accuracy based on local oscillator drift and precision. The use of this RF carrier phase measurement requires that the receiver determine exactly which wavelength the hardware is receiving. The disadvantage of this technique is that the position will be off by a GPS wavelength of roughly 20 centimeters if it assumes it is receiving a different wavelength. This problem, known as the integer ambiguity problem, is generally solved statistically in one of several ways by the RTK positioning algorithm (15) (16).

**ION Autonomous Robotic Lawn Mower Competition**

The ION started the annual autonomous robotic lawn mower competition in order to increase research in the field of positioning, navigation, and timing. A secondary goal of the event is to provide an incentive for college students to learn the skills needed to be proficient in the field of autonomous navigation systems (17).

The annual competition includes a predefined mowing field that is to be mowed by each team’s autonomous robot lawn mower. Each team aims to mow the entire provided
mowing plot without going outside the boundary, colliding with the fence or flower bed, or striking the moving obstacle (18).

The majority of teams at the competition utilize RTK GPS receivers to enable precise robot navigation. Commercial GPS receivers that provide an RTK solution quality at the centimeter level of accuracy generally cost tens of thousands of dollars. This large cost is a barrier to entry for new teams to succeed. This illustrates the need to commercialize RTK GPS positioning technology.

**Commercialization of Navigation Technology**

**Handheld Navigation Systems**

In the early 1990s, companies such as Garmin and Trimble began mass producing consumer-priced GPS receivers. The handheld devices were very popular with military personnel serving in Kuwait and Saudi Arabia in the 1991 Gulf War. In the early 2000s, products marketed towards athletes, such as the wrist-worn Forerunner, could provide GPS logging capabilities to recreational runners. Garmin has demonstrated successful integration of GPS technology with preexisting fish finder and avionics products. In 2005, Garmin released standalone GPS navigators for automobile navigation use.

One benefit of handheld navigation systems is that the dynamics of the receiver are known to be no faster than pedestrian, bicycle, or automobile navigation speeds. This allows some constraint on the GPS solution. Further constraints on navigation-based receivers make assumptions that your position is always on a segment of an *a priori* map. This information helps constrain unrealistic uncertainties in the GPS position solution.
**Car and Cell Phone Navigation Systems**

Cell phones that integrate GPS commonly use network AGPS. The satellite navigation data is transmitted via the cellular network to the end user’s device. The receiver can provide a very fast TTFF since the receiver doesn’t have to download the almanac data from the satellite network – which can otherwise take upwards of 12.5 minutes. Cell phone networks can be used to provide a DGPS service based on ground reference stations. Instead of using the satellite-based broadcast approach used in SBAS, the cellular network is used to provide precise ephemeris corrections from a network of ground reference stations.

**Consumer Products**

*John Deere/NavCom Technology*

John Deere, longtime manufacturer of agricultural equipment, has been selling GPS-based navigation systems for their agricultural equipment. To enable this line of products, John Deere purchased NavCom Technology. The onboard navigation systems include a GPS receiver and a touch screen color display for the operator to interact with the equipment. Embedded autonomous navigation algorithms aid farmers to drive straighter lines, and as a result, yield is maximized.

NavCom Technology’s receivers utilize a proprietary ground-based observation network to provide a precise SBAS correction to their client’s receivers. NavCom Technology claims less than 10 centimeter accuracy in each horizontal axis (19).
**Husqvarna**

Husqvarna sells a consumer autonomous robot lawn mower. As of June 2011, they sell three models with varying feature sets. The mowers use a buried wire to navigate within an end user’s lawn. Features include automatic charging, all-electric operation, anti-theft alarm, weather proofing, solar charging, and cell phone connectivity (20).

**Friendly Robotics**

Friendly Robotics sells four models of autonomous robot lawn mowers. They depend on a buried wire to be placed around the lawn’s perimeter and routed around any obstacle shorter than six inches. Friendly Robotics claims that the mowers include a “compass-like” device that helps the unit navigate (21).

**Evolution Robotics**

Evolution Robotics sells an autonomous floor cleaner for use indoors. The floor cleaner uses a novel navigation method of projecting a light pattern on the ceiling in the room of operation. The robot uses an IR detector to measure the image above the robot and compute the location of the robot. This enables the robot to drive precisely indoors. Evolution Robotics is actively marketing several types of navigation technologies to other original equipment manufacturers for integration in 3rd party robotics products (22).

A void currently exists in consumer products that utilize GNSS as a method for precise navigation of autonomous outdoor mobile robots. This thesis demonstrates successful
implementation of exactly this goal by integrating technology conventionally used for consumer handheld navigation products with an existing mobile robot platform.
CHAPTER 3: CWRU CUTTER’S ARCHITECTURE

Mechanical Design

CWRU Cutter is built around an MTD Products Incorporated walk-behind electric lawn mower deck. The deck has been engineered for consumer applications and features CycloCut technology. The product is sold with a 19 inch blade driven by a 24V permanent magnet motor. The inclusion of an electric mower deck over a gas-powered model provides many benefits – including reduced vibration and noise, and the elimination of a fuel system.

A string trimmer is mounted on the robot’s right side. This allows CWRU Cutter to edge effectively to increase the final quality of the field. The string trimmer is a commercial trimmer head attached to a 20 volt motor provided by MTD Products Incorporated. The trimmer is hard-mounted to the robotic platform at a fixed height appropriate for trimming operations.

The drive motors used on CWRU Cutter are sourced from Invacare Incorporated, which is a local electric wheelchair manufacturer. These motors allow the robot to drive up and down inclines as well as navigate safely over ruts and other obstacles without decreasing speed. This is a vast improvement over previous versions of the CWRU Cutter platform that notoriously struggled to move and pivot over rough terrain and in heavy grass. CWRU Cutter IV’s drive wheels, provided by MTD Products Incorporated, feature a wide dirt tread. Table 1 outlines CWRU Cutter IV’s mechanical specifications and measurements.
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<td>Overall Width</td>
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<td>Max Angular Speed</td>
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</table>

**Table 1**: CWRU Cutter IV's mechanical dimensions.

The mechanical design of CWRU Cutter IV is shown in Figure 2. The resulting fabrication of CWRU Cutter IV is shown in Figure 1.

**Figure 2**: A CAD render of CWRU Cutter IV.

**Figure 1**: CWRU Cutter IV at the mowing competition.
Electrical Design

E-Stop and Safety System

CWRU Cutter has two E-Stop safety chains. If any component in either chain is disabled, the corresponding subsystem is deactivated. The master E-Stop chain controls power delivered to the drive wheels. The master E-Stop is also a dependency of the blade/trimmer E-Stop chain.

The master E-Stop chain requires the following enabled circuits for operation:

1. Main E-stop Switch
2. Software Controlled Master Enable Relay
3. Remote E-Stop Relay

The robot has a low-level safety state machine that governs the software-activated E-Stop circuit. The safety state machine allows the robot to drive only after five seconds of audible alert via a siren. The controller must also provide a continuous “heartbeat” monitored via a FPGA-level watchdog timer for the software enable relay to be activated.

The blade E-Stop chain requires the following enabled circuits for operation:

1. Blade E-Stop Switch
2. Master E-Stop Relay
3. Software Controlled Blade and Trimmer Relays
**Speed Controller Selection**

The selection of speed controllers directly affects several factors of CWRU Cutter, including controllability, durability, and safety. A variety of speed controllers have been tested. Victor speed controllers, sold by Vex Robotics (23), are robust against failure but exhibit a highly nonlinear control response, which makes their use in a closed-loop control system difficult. Dimension Engineering Sabertooth 2x25 speed controllers are very linear and have a variety of input options (24). However, the Sabertooth controllers are less robust and have failed on previous versions of CWRU Cutter. A Roboteq AX2550 speed controller is used for the drive wheels. The Roboteq controller includes a variety of input options, internal circuit protection, a robust form factor, and excellent response characteristics (25). The Victor speed controller was chosen to soft-start the string trimmer and main cutting blade of CWRU Cutter IV.

**Battery Selection**

All motor and electronics power on the vehicle comes from two 12 volt OPTIMA YellowTop marine batteries (26). The batteries are connected in series and provide the robot with a 24 volt power system providing 38 amp-hours of power.

Primary consideration was given to power retention and maintenance. Lead-acid batteries are capable of retaining their charge for approximately two months. This makes them ideal for lawn mowing applications. Batteries with alternative chemistries can offer more capacity for equal volume and mass, though the lower cost and less complicated charging requirements led to the decision of lead-acid batteries for CWRU Cutter IV.
**Computational Platform Selection**

CWRU Cutter IV uses a National Instruments sbRIO for robust real-time control. The NI sbRIO platform includes two computational subsystems: a 40 MHz FPGA and a 500 MHz RT processor. The FPGA implements application-specific high-speed timing, data acquisition, and control functionality. The real-time processor, using sensor data acquired by the FPGA, implements higher-level algorithms and outputs subsequent control commands to the FPGA. The combination of these two devices allow for a robust software platform.

The FPGA on the sbRIO interfaces directly to 110 3.3V DIO pins that are capable of operating at speeds up to 10 MHz. The FPGA also interfaces directly to up to three National Instruments C-series I/O modules that include signal conditioning (27).

The Embedded Vision System facilitates an interface with standard Firewire and/or Gigabit Ethernet cameras for image acquisition. The EVS-1464 includes an Intel Core 2 Duo processor and runs the LabVIEW Real-Time module to accomplish machine vision processing with low jitter and latency (28).

CWRU Cutter IV includes a touch panel for interaction with the user. The touch panel selected is a QSI Corporation QTERM-A7. The unit runs Windows Embedded CE 6.0 and executes LabVIEW applications deployed from the LabVIEW touch panel module. The unit selected has NEMA-4X and IP66 ratings, which enable its exposure to water, dust, and heat (29). Problems with spurious emissions caused the touch panel to remain largely unused. Specifically, the touch panel would cause the GPS receivers on the robot
to lose lock on satellite signals. This level of interference was unacceptable and left for future investigation.

A Dell Latitude E6500 laptop connected via 802.11n wireless network switch is used for data logging, path planning, and additional GUI (graphical user interface) applications.

Platform Sensors

GPS

Two GPS receivers are used to provide the robot with a global estimate of position, velocity, and heading. RTK DGPS has been selected to minimize the effects of ionospheric lensing and stratospheric bias. The L2C civilian frequency band, used to receive Omnistar HP corrections, allows for further conditioning of position solutions.

The selected GPS receivers are Novatel ProPak-V3 units and run Novatel’s proprietary dual-frequency RT-2 firmware. The base station GPS antenna, used for real-time differential GPS corrections, is mounted on a fiberglass surveying tripod and is anchored within fifty meters of the operating area. A set of Freewave FGR-115RC RS-232 serial packet radios periodically transmit corrections from the base station’s GPS receiver to the rover (30). The corrections are used by the Novatel receiver firmware to provide a RTK (Real-Time Kinematic) GPS solution that has 1 cm + 1 ppm accuracy (15).

In order to evaluate low-cost GPS alternatives, an InStock Wireless GPS310 RF power splitter is used to split the RF signal from one active GPS antenna to three GPS receivers (31).
**IMU**

An IMU is mounted on the robot. The selected IMU, a Cloud Cap Technology Christa IMU, is a six-axis unit that utilizes automotive-grade MEMS sensors to provide angular velocity and acceleration in each egocentric Cartesian axis. The IMU provides real-time 6-DOF inertial measurement at 100Hz via RS-232 serial (32).

**Encoders**

Encoders attached to the motor shaft of the drive wheels provide wheel speed and wheel position information. The encoders chosen for the application are Grayhill 63R256 256-count quadrature encoders (33). A 24 to 1 transmission on the output of the motor provides approximately 23,626 ticks/meter. The large number of ticks per revolution allows for backwards differentiation of the position with respect to time. This differenced value can be used directly as a motor velocity for control purposes. The large number of counts per meter also assists with egocentric integration of the robot’s position over time.

**LIDAR**

CWRU Cutter IV utilizes a SICK LMS-291 Light Detection and Ranging (LIDAR) unit mounted on the front of the robot. The LIDAR unit delivers a 180° field of view, 8 m range scans, and 1° resolution at roughly 9 Hz on a 38.4 kbps RS-232 connection to the sbRIO (34).
**Cameras**

Two forward-facing FireWire cameras are mounted to the top front corners of the robot. The Imaging Source DFK 21AF04 FireWire cameras (35) equipped with CBC America Corporation 1/3 1.8-3.6MM FL.6 lenses capture 640x480 RGB color images at a rate of 10 Hz for analysis on the EVS. The mounting positions and the wide angle of the lenses allow for at least 180° of viewing area in front of the robot up to a range of about 2 meters.

**Bump Sensors**

A new feature to CWRU Cutter IV is the addition of a contact sensor for obstacle avoidance. The sensor consists of a flexible bumper suspended from the robotic platform by leaf springs. Industrial limit switches provide bump sense data to the robot.

**Electronics Architecture**

A system-level hardware architecture has been designed to allow for independent development of components and is presented in Figure 3.

A modular architecture with well-defined interfaces allows for independent development of components that can be easily interchanged in order to characterize performance of any one method that can be used to accomplish a particular task.

Each computational platform will be outlined according to the tasks assigned to it.
Figure 3: CWRU Cutter IV's electronics architecture.

**Spine (NI sbRIO)**

The sbRIO PAC ensures safety and low-level autonomy for CWRU Cutter. It accomplishes a variety of tasks:

1. **Sensor Drivers**

   GPS, IMU, LIDAR, and encoder messages are parsed in the FPGA. All critical data for low-level control of the robot is parsed at this low hardware level to avoid communication problems and latency.
2. **PID Wheel Speed Control**

Wheel velocity is controlled using a PID loop that operates on the FPGA at 100 Hz. Velocity commands are processed at a rate of 10 Hz from the RT control loop.

3. **Safety State Machine**

Several safety requirements are checked in the FPGA to ensure safe robot operation. A heartbeat is triggered from the real-time controller at 10 Hz to indicate an error has not occurred and that the main control program is running. If this signal is not received in .25 seconds, the mower is immediately paused. The states of the E-Stop chains are measured at 10 Hz and are used as signals to pause the robot if required.

4. **Physical State Observer**

A variety of sensors are available for use in robot positioning. A KF is used to probabilistically determine the most likely state estimate. The design of the Physical State Observer is described in detail in Chapter 4.

5. **Path Driver**

A major design goal for CWRU Cutter is to mow straight and parallel paths, as opposed to random paths. Other commercial autonomous mowers only demonstrate the ability to follow a buried guiding cable or drive random paths. The path driver supports five path primitives:

   a. **Line**

      The line segment is defined by its start and end Cartesian coordinates.
b. Arc

The arc is defined by the arc center’s Cartesian coordinates and the exit point’s Cartesian coordinates.

c. Pivot

The pivot is defined by a direction and an exit heading.

d. Linear Velocity and Angular Rate Pair

A linear velocity and angular rate pair are used to navigate for a specified duration.

e. Stop

The stop command stops the robot for a given duration.

The path driver uses three control terms:

a. Heading difference error

b. Perpendicular distance to path primitive error

c. Damping term on curvature

(36) formally introduces the path driving algorithm chosen, including stability derivation.

6. Polar Freespace Observer

The Polar Freespace Observer acts as a filter on obstacle field observations as reported by the EVS, LIDAR, and bump sensors. Subsequent obstacle fields are projected forward by the backward difference of the robot’s pose. This helps to removes noise in obstacle detection and provides obstacle information in the case
of sensor failure if the obstacle has previously been observed. The most important function of the Polar Freespace Observer is that the area next to the robot and behind the robot, while unobserved by sensors, is continually tracked for reflexive obstacle avoidance.

7. Reflexes

Local reflexive obstacle avoidance has been implemented to provide CWRU Cutter with a “hand on the wall” obstacle avoidance behavior. In order for this process to occur at a rate of 10 Hz, configuration spaces of the robot are pre-computed in the same polar representation as the Polar Freespace. Two reflexes use the robot’s local body definition and speed-interpolated, velocity-dependent, configuration spaces to constrain the path driver’s linear and angular velocity commands. The two reflexes are the “veer left” reflex and the “stop” reflex.

a. Veer Left Reflex

The veer reflex performs an element-wise comparison between the Polar Freespace Observation and current speed-interpolated, velocity-dependent, configuration space. If the obstacle field intersects the scaled configuration space, an iterative search is performed while decreasing linear velocity and increasing angular velocity. This causes the robot to slow down and turn to the left of observed objects.

b. Stop Reflex

The stop reflex performs a comparison of the robot’s tight body configuration space with the most recent Polar Freespace Observation. If
an intersection is found, the robot is decelerated along a constant curvature path until it is stopped. This causes the robot to slow down along the commanded path (while continuing to avoid any obstacle the veer left reflex is obeying) while saving the robot from a collision.

More details on the reflexes implemented in CWRU Cutter’s navigation architecture can be found in (2).

*Eyes (NI EVS)*

The EVS captures images from two cameras at 10 Hz and processes them in real time using SVM Feature Classification. Details on texture identification and feature classification will be the topic of a future thesis.

The cameras are located at the top left and right front corners of the robot and are angled down and in so that at least 180° in front of the robot can be observed. The cameras have been calibrated to allow for conversion of pixel (i,j) coordinates to real-world (x,y) coordinates in meters. The calibration routine also removes the fish-eye effect that wide-angle lenses introduce.

*Brain (Dell E6500 Laptop)*

A Dell Latitude E6500 Laptop is connected to the mower via a 802.11n wireless network. It performs tasks that are computationally intensive and less critical to the lawn mower’s real-time operation.
1. Logging

The laptop receives 10 Hz data logs from the sbRIO and EVS. This real-time logging allows for post-run playback of data to enable debugging and algorithm improvement.

2. Dynamic Path Planning

The laptop will eventually perform dynamic path planning. This topic will be the topic of a future thesis.

The Athena Navigation System

**Hardware and Part Selection**

The prototype ANS is comprised of two ANBs, two GPS signal splitters, two GPS antennas, and two wireless routers.

Each ANB includes a u-blox LEA-6T GPS receiver module and support electronics. A COTS PoE module provides 12 watts of power at 5 volts from an external 802.3af-compliant Ethernet switch. A COTS ARM CPU macromodule runs an embedded variant of the Debian Linux operating system. A variety of sensors are supported in the hardware layout, but the firmware utilizes only the u-blox GPS receiver at this time.

**GPS RF Layout**

Close attention is required in the layout of the RF traces on the ANB. At GPS frequencies, the traces act as a transmission line. As a result, the traces must be the proper width and etched on a controlled-dielectric PCB (37).
Software Build Environment

The popular Eclipse IDE, in conjunction with the CDT (C/C++ Development Tooling) module, allows for Windows users to cross-compile executables for ARM targets running on Linux (38). Interactive debugging is enabled using gdbserver over RS-232 serial or TCP/IP networking.

Software

RTKLIB is a GNU GPLv3 open source GNSS positioning library written in portable C.

RTKLIB is available from (16) and has been compiled using the Eclipse IDE software environment for ARM Linux.

RTKLIB provides a variety of utility functions that permit stream-to-stream communication. For example, a serial device on an embedded device can be used as a stream source in order to transmit raw GPS data to a laptop running the RTKLIB positioning software. Built-in visualization tools allow for a user to see real-time data and system status. The software library provides open source positioning algorithms for single-point receiver positioning, DGPS/DGNSS positioning, and RTK positioning. Finally, it provides interface with a variety of proprietary binary data formats. RTKLIB can be configured to output NMEA-format position logs via TCP network stream.
CHAPTER 4: CWRU CUTTER’S PHYSICAL STATE OBSERVER

State Definition and Coordinate Frame

The robot’s position, velocity, and attitude are collectively referred to as the robot’s Physical State. More specifically, the Physical State is defined as

\[
\mathbf{x} = \begin{bmatrix} x & y & z & v_x & v_y & v_z & \theta & \varphi & \psi & \omega_x & \omega_y & \omega_z \end{bmatrix}^T
\]

(1)

where \( x, y, \) and \( z \) are the position of the robot in Cartesian coordinates referenced to a local coordinate frame origin. The coordinate frame of the robot is orthogonal to a conventional ENU (East, North, Up) coordinate frame such that \( x \) and \( y \) track the number of meters East and North of the coordinate frame origin. \( v_x, v_y, \) and \( v_z \) measure the velocities of the robot in meters/second. \( \theta, \varphi, \) and \( \psi \) measure the roll, pitch, and yaw angles of the robot in radians as referenced to the local coordinate frame origin. \( \omega_x, \omega_y, \) and \( \omega_z \) measure the angular rates in the roll, pitch, and yaw angles. This vector adequately describes the motion of the robot by defining the positions and velocities in all six Cartesian degrees of freedom.

Kalman Filter

In order to remove observation noise from sensor data, a KF is employed. The KF estimates the true value of the state vector defined in Equation (1) with a given a set of measurements that provide observability of those state variables, or a state variable’s integral or derivative.
The KF has two algorithmically important components. The first component is a stochastic predictor that runs every control cycle in order to form a ballistic estimate of the state based on an iterative system model and control inputs. The second component corrects the predicted solution estimate with sensor measurements as they are received. For purely linear systems, the KF does not require sensors measurements to come at a predefined rate or in any particular order. The KF is redefined here from (39).

A dynamic system is defined that follows the standard form

\[ \mathbf{x}_k = f_k \mathbf{x}_{k-1} + B_k \mathbf{u}_{k-1} + \mathbf{w}_k \]  

(2)

where \( f_k \) is a matrix that transforms \( \mathbf{x}_{k-1} \), the state at iteration \( k - 1 \), to the state \( \mathbf{x}_k \) at iteration \( k \), \( B_k \) is a matrix that transforms the control model \( \mathbf{u}_{k-1} \) to the state, and \( \mathbf{w}_k \) is the process noise according to

\[ \mathbf{w}_k \sim \mathcal{N}(0, \mathbf{Q}_k) \]  

(3)

where \( \mathbf{Q}_k \) defines the covariance matrix of the zero mean Gaussian noise of the process.

An observation of a state variable can be represented in the the form

\[ \mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k \]  

(4)

where \( \mathbf{z}_k \) is the sensor measurement, \( \mathbf{H}_k \) is the sensitivity of the state to the measurement, and \( \mathbf{v}_k \) is measurement or observation noise that is described by
\[
\mathbf{v}_k \sim N(0, \mathbf{R}_k)
\]  

(5)

where \( \mathbf{R}_k \) defines the covariance matrix of the zero mean Gaussian noise of the observation.

The first KF step is the predictor and is defined by

\[
\begin{align*}
\mathbf{x}_k^\prime &= \mathbf{f}_k \mathbf{x}_{k-1} + \mathbf{B}_k \mathbf{u}_{k-1} \\
\mathbf{P}_k^\prime &= \mathbf{f}_k \mathbf{P}_{k-1} \mathbf{f}_k^T + \mathbf{Q}_k
\end{align*}
\]

(6)

where \( \mathbf{x}_k^\prime \) is the a priori predicted state, \( \mathbf{P}_k^\prime \) is the a priori state’s predicted covariance matrix, and \( \mathbf{P}_{k-1} \) is the previous iteration’s final covariance matrix.

When a measurement is available, the second KF step is executed. The update equations can be applied as many times as needed to account for all available sensor measurements. It is often convenient to split large measurement vectors into multiple updates if the measurements are uncorrelated.

The KF update equations are

\[
\begin{align*}
\mathbf{y}_{\cdot k} &= \mathbf{z}_k - \mathbf{H}_k \mathbf{x}_k^\prime \\
\mathbf{S}_k &= \mathbf{H}_k \mathbf{P}_k^\prime \mathbf{H}_k^T + \mathbf{R}_k \\
\mathbf{K}_k &= \mathbf{P}_k^\prime \mathbf{H}_k^T \mathbf{S}_k^{-1} \\
\mathbf{x}_k^* &= \mathbf{x}_k^\prime + \mathbf{K}_k \mathbf{y}_{\cdot k} \\
\mathbf{P}_k^* &= (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{P}_k^\prime
\end{align*}
\]

(7)
where $y_k$ is the innovation, or difference, between the observation and predicted a priori state, $S_k$ is the covariance innovation, $K_k$ is the optimal Kalman gain, $x_k^+$ is the a posteriori state estimate, and $P_k^+$ is the a posteriori covariance estimate.

**System Model**

The control input of the robot platform is defined as

$$u_k = \begin{bmatrix} v \\ \omega \end{bmatrix}$$

where $v$ and $\omega$ are linear and angular velocities in the robot's egocentric coordinate frame.

The dynamic model matrices $f_k$ and $B_k$ for the state vector defined in Equation (1) and the control inputs defined in Equation (8) are

$$f_k = \begin{bmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - \tau_v & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 - \tau_v & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 - \tau_v & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 - \tau_v & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 - \tau_v & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 - \tau_v & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 - \tau_v \end{bmatrix}$$

$$(9)$$
\[
B_k = \begin{bmatrix}
0 & 0 & 0 & \tau_v \cos \tilde{\psi} & \tau_v \sin \tilde{\psi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tau_{\omega}
\end{bmatrix}^T
\] (10)

where \(\Delta t\) is the measured time since the predictor was last run, \(\tau_v\) and \(\tau_{\omega}\) are parameters that weight an average between the command’s and the state’s respective linear and angular velocities, and \(\tilde{\psi}\) is an average of the robot’s yaw from iteration \(k - 1\) and the heading estimated by pure time integration of the previous angular rate command.

Finally, the covariance of the process noise is defined as

\[
Q_k = \begin{bmatrix}
\sigma_v^2 \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & \sigma_v^2 \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & \sigma_v^2 \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & \sigma_{\omega}^2 \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & \sigma_{\omega}^2 \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & \sigma_v^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & \sigma_v^2 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\omega}^2 & 0 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\omega}^2 & 0 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\omega}^2 & 0 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\omega}^2 & 0 & 0
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_{\omega}^2
\end{bmatrix}
\] (11)

where \(\sigma_v\) and \(\sigma_{\omega}\) are tuning constants that continually increase the error in the respective linear and angular velocity state variables covariance estimates due to the inclusion of the control term in Equation (10).
Sensor Inputs

For each $i^{th}$ sensor input, the observation vector $\mathbf{z}_i$, the covariance matrix $\mathbf{R}_i$, and the observation’s sensitivity to the state $\mathbf{H}_i$ are defined. A short description of the observation is also provided.

Novatel GPS Position

The Novatel GPS receiver provides positional updates at a rate of 10 Hz through the binary log message BESTPOSB:

$$\mathbf{z}_{\text{Novatel,BESTPOSB}} = \begin{bmatrix} x_{\text{Novatel,BESTPOSB}} \\ y_{\text{Novatel,BESTPOSB}} \\ z_{\text{Novatel,BESTPOSB}} \end{bmatrix}$$  \hfill (12)

This message includes standard deviation estimates of the position solution in both the Northing and Easting directions. A constant standard deviation is assigned to the vertical measurement:

$$\mathbf{R}_{\text{Novatel,BESTPOSB}} = \begin{bmatrix} \sigma^2_{\text{Novatel,BESTPOSB,Easting}} & 0 & 0 \\ 0 & \sigma^2_{\text{Novatel,BESTPOSB,Northing}} & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix}$$  \hfill (13)

The three positions from the observation map directly to the state:

$$\mathbf{H}_{\text{Novatel,BESTPOSB}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$  \hfill (14)
**Novatel GPS Velocity and Heading**

The Novatel GPS receiver provides speed measurements in both the horizontal and vertical directions as well as a heading measurement at a rate of 10 Hz through the binary log message BESTVELB:

\[
\mathbf{z}_{\text{Novatel,BESTVELB}} = \begin{bmatrix}
V_{\text{Novatel,BESTVELB, horizontal}} \\
V_{\text{Novatel,BESTVELB, vertical}} \\
\psi_{\text{Novatel,BESTVELB}}
\end{bmatrix}
\]  

(15)

Constant standard deviations are assigned to both the horizontal and vertical velocity components. A piecewise velocity-dependent standard deviation on heading is defined:

\[
\sigma_{\text{Novatel,BESTVELB,sp}}(\dot{\psi}_{k-1}) = \begin{cases} 
0.5 & \dot{\psi}_{k-1} > 0.5 \\
(\dot{\psi}_{k-1} - 0.5)^2 \cdot 100 + 0.5 & \dot{\psi}_{k-1} \leq 0.5
\end{cases}
\]  

(16)

where \( \dot{\psi}_{k-1} = \sqrt{v_{x,k-1}^2 + v_{y,k-1}^2} \) and \( v_{x,k-1}, v_{y,k-1} \) are velocity components from the a posteriori state estimate from iteration \( k-1 \).

The resulting covariance matrix is

\[
\mathbf{R}_{\text{Novatel,BESTVELB}} = \begin{bmatrix}
\sigma_{\text{horiz}}^2 & 0 & 0 \\
0 & \sigma_{\text{vert}}^2 & 0 \\
0 & 0 & \sigma_{\text{Novatel,BESTVELB,sp}}^2(\dot{\psi}_{k-1})
\end{bmatrix}
\]  

(17)

The three measurements map to four state variables:
\[
\mathbf{H}_{\text{Novatel,BESTVELB}} = \begin{bmatrix}
0 & 0 & 0 & \cos \psi_{k-1} & \sin \psi_{k-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
\end{bmatrix}
\]

where $\psi_{k-1}$ is the heading from the \textit{a posteriori} state estimate at time $k-1$.

**Cloud Cap Technology Christa IMU Angular Rate**

The Cloud Cap Technology Christa IMU provides angular rate information in the robot’s egocentric coordinate frame at a rate of 100 Hz. For simplicity, the robot’s roll and pitch angles are assumed be close to zero so that the angular rate in the IMU’s z-axis represents the robot’s angular rate in the global z-axis. Furthermore, the controller chooses the most recent IMU message to be used as an update at the control rate of 10 Hz.

\[
z_{\text{IMU,Angular Rate}} = \begin{bmatrix} \omega_{\text{IMU,z}} \end{bmatrix}
\]

(19)

A constant standard deviation is assigned to the rate measurement. As a result, the measurement’s covariance matrix is

\[
\mathbf{R}_{\text{IMU,Angular Rate}} = \begin{bmatrix} \sigma^2_{\text{IMU,Angular Rate}} \end{bmatrix}
\]

(20)

The sensitivity to the state is simply

\[
\mathbf{H}_{\text{IMU,Angular Rate}} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

(21)
**Wheel Encoder Velocities**

The wheel speeds are measured at a rate of 100 Hz. The controller chooses the most recent wheel speed measurement to be used as an update at the control rate of 10 Hz.

\[
Z_{\text{Wheel Speeds}} = \begin{bmatrix} v_{\text{Left}} \\ v_{\text{Right}} \end{bmatrix}
\]  

(22)

A constant standard deviation is assigned to each wheel speed measurement. As a result, the measurement’s covariance matrix is

\[
R_{\text{Wheel Speeds}} = \begin{bmatrix} \sigma_{\text{Wheel Speed}}^2 & 0 \\ 0 & \sigma_{\text{Wheel Speed}}^2 \end{bmatrix}
\]  

(23)

The wheel speeds update both the Northing and Easting velocity components as well as the robot’s angular rate.

\[
H_{\text{Wheel Speeds}} = \begin{bmatrix} 0 & 0 & 0 & .5 \cdot \cos \psi_{k-1} & 0 & 0 & 0 & 0 & 0 & 0 & -1/T \\ 0 & 0 & 0 & .5 \cdot \sin \psi_{k-1} & 0 & 0 & 0 & 0 & 0 & 0 & 1/T \end{bmatrix}
\]  

(24)

where \( T \) is the track width of the robot.

**RTKLIB NMEA GPGGA Message**

The RTKLIB software library outputs three-dimensional ENU positional updates via NMEA GPGGA messages at a rate of 10 Hz. A heading estimate from the change in position is calculated as a fourth measurement due to the fact that the RTKLIB NMEA GPRMC heading estimate is incorrect.
\[ \tilde{\psi}_{\text{NMEA,GPGGA}} = \text{atan2}(\Delta y_{\text{NMEA,GPGGA}}, \Delta x_{\text{NMEA,GPGGA}}) \]  

(25)

where \( \text{atan2} \) is the two-input four-quadrant continuous arctangent.

\[
\begin{bmatrix}
\bar{x}_{\text{NMEA,GPGGA}} \\
\bar{y}_{\text{NMEA,GPGGA}} \\
\bar{z}_{\text{NMEA,GPGGA}} \\
\bar{\psi}_{\text{NMEA,GPGGA}}
\end{bmatrix} =
\begin{bmatrix}
\Delta x_{\text{NMEA,GPGGA}} \\
\Delta y_{\text{NMEA,GPGGA}} \\
\Delta z_{\text{NMEA,GPGGA}} \\
\Delta \psi_{\text{NMEA,GPGGA}}
\end{bmatrix}
\]  

(26)

A standard deviation of position is selected according to the fix quality \( Q \) as indicated in the message. The positional standard deviation can be described piecewise:

\[
\sigma_{\text{NMEA,GPGGA}}(Q) =
\begin{cases}
\infty & \text{Invalid} \\
8 & \text{Single} \\
8 & \text{Differential} \\
8 & \text{Differential} \\
.2 & \text{RTK Floating Integer Ambiguity} \\
.1 & \text{RTK Fixed Integer Ambiguity}
\end{cases}
\]  

(27)

A piecewise velocity-dependent standard deviation on heading from Equation (16) is utilized.

The covariance matrix is then defined as

\[
R_{\text{NMEA,GPGGA}} =
\begin{bmatrix}
\sigma_{\text{NMEA,GPGGA}}^2(Q) & 0 & 0 & 0 \\
0 & \sigma_{\text{NMEA,GPGGA}}^2(Q) & 0 & 0 \\
0 & 0 & \sigma_{\text{NMEA,GPGGA}}^2(Q) & 0 \\
0 & 0 & 0 & \sigma_{\text{NMEA,GPGGA},\phi}(\delta_{k-1})
\end{bmatrix}
\]  

(28)
The four measurements map linearly to the state:

\[
H_{\text{Wheel Speeds}} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\] (29)

**RTKLIB NMEA GPRMC Message**

The RTKLIB software library outputs velocity and heading measurements at a rate of 10 Hz via NMEA GPRMC messages. The heading measurement is incorrect and unused in this implementation.

The horizontal speed measurement is the only measurement defined:

\[
z_{\text{NMEA,GPGGA}} = \begin{bmatrix} v_{\text{NMEA,GPGGA, horizontal}} \end{bmatrix}
\] (30)

The standard deviation is assigned a constant value and as a result the covariance matrix is

\[
R_{\text{NMEA,GPRMC}} = \begin{bmatrix} \sigma_{\text{speed}}^2 \end{bmatrix}
\] (31)

Finally, the sensitivity to the state is

\[
H = \begin{bmatrix} 0 & 0 & 0 & \cos \psi_{k-1} & \sin \psi_{k-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
\] (32)
CHAPTER 5: RESULTS

Path for Analysis

The path chosen for comparison of navigation technologies is a series of lines and arcs and is pictured in Figure 4:

![Cartesian graph of the path chosen for autonomous navigation.](Figure 4)

**Figure 4:** The Cartesian graph of the path chosen for autonomous navigation.

Navigation with Novatel RTK GPS

The robot was allowed to autonomously navigate the path presented in Figure 5 using the reference system platform consisting of the Novatel GPS receiver in RTK mode and the Cloud Cap Technology Christa IMU. Data was logged and post-processed to measure the navigation success of the robot.

The data for this section come from the log titled 11_06_12--22_58_38$1640_025822.$
The data for this section were recorded between June 12th, 2011 at 9:58pm and 10:08pm.

The top-down Cartesian view of the robot’s position trail is presented in Figure 5:

**Figure 5**: Cartesian plot of robot position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Dotted Purple: Commanded path.)

The X and Y Cartesian components, as a function of time, are presented separately in Figure 6 and Figure 7:

**Figure 6**: The X (Easting) component of position. (Black: Physical State Position, Red: Novatel RTK GPS Position)
Figure 7: The Y (Northing) component of position. (Black: Physical State Position, Red: Novatel RTK GPS Position)

In order to measure the success of the robot’s navigation capability, the X and Y components of the Physical State Observer’s state estimate are compared to the nearest point on the commanded path and shown over time. The RMS of this residual over the navigation of one complete cycle of the commanded path is used to benchmark the performance capability of the robot using the reference sensor platform and is presented in Figure 8.

Figure 8: The X and Y residuals shown (in Black and Red respectively) are measured from the Physical State Obsever estimate of position to the nearest point on the commanded path.

For this particular set of data, the RMS position error is 4.88 centimeters.
The speed trajectory for one cycle of navigation of the commanded path is presented in Figure 9:

**Figure 9:** The speed trajectory for one cycle of navigation of the commanded path. (Black: Physical State Speed, Red: Novatel RTK GPS Speed, Purple: Commanded speed.)

In order to measure the quality of the robot’s closed loop speed control, the Physical State Observer’s speed estimate is compared with the commanded speed from the path driver. The RMS of this residual over the entire navigation of one complete cycle of the commanded path is used to benchmark the performance of the robot’s closed loop speed control. The velocity residual is presented in Figure 10:

**Figure 10:** The speed residual shown (in Black) is measured from the Physical State Observer estimate of speed to the commanded speed.

For this particular set of data, the RMS Speed Error is 3.71 centimeters/second.
The angular rate trajectory for one cycle of navigation is presented in Figure 11:

![Angular Rate Trajectory](image1)

**Figure 11:** The angular rate trajectory for one cycle of autonomous navigation. (Black: Physical State Angular Rate, Red: Cloud Cap Christa IMU Angular Rate, Purple: Commanded angular rate.)

In order to measure the quality of the robot’s closed loop angular rate control, the Physical State Observer’s angular rate estimate is compared with the commanded angular rate from the path driver. The RMS of this residual over the entire navigation of one complete cycle of the commanded path is used to benchmark the performance of the robot’s closed loop angular rate control. The angular rate residual is presented in Figure 12:

![Angular Rate Residual](image2)

**Figure 12:** The angular rate residual shown (in Black) is measured from the Physical State Observer estimate of angular rate to the commanded angular rate.

For this particular set of data, the RMS angular rate error is 0.0654 radians/second.

The heading trajectory for this set of data is presented in Figure 13:
Figure 13: The heading trajectory for one cycle of navigation. (Black: Physical State Heading, Red: Novatel RTK GPS Heading, Purple: Heading of closest path segment perpendicular to robot's position.)

In order to measure the quality of the robot’s closed loop heading control, the Physical State Observer’s heading estimate is compared with the tangential heading of the closest point on the commanded path primitive. The RMS of this residual over the entire navigation of one complete cycle of the commanded path is used to benchmark the performance of the robot’s closed loop heading control. The heading residual is presented in Figure 14.

Figure 14: The heading residual shown (in solid black) is measured from the Physical State Observer estimate of heading to the heading of the closest path element. Dotted black shows the standard deviation estimate of the heading term from the Physical State Observer.

For this particular set of data, the RMS heading error is 0.0636 rad.
For this entire set of data, the Novatel RTK GPS Solution tracked a constant number of ten satellites as presented in Figure 15:

**Figure 15:** The number of satellites tracked over time by the Novatel RTK GPS solution.

**RTKLIB u-blox GPS Solutions**

Next, RTKLIB’s solution for position is presented under the circumstances that no differential corrections are performed. That is, the u-blox data of only the rover is used to compute a GPS solution. The following graph, Figure 16, includes the same reference system sensors from Figure 5, but also includes the ANB’s solution for position:
Figure 16: Cartesian plot of robot position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Dotted Purple: Commanded path, Green: RTKLIB Single Receiver Position Estimate.)

It is notable to observe two things from Figure 16. The first is that there is a large amount of noise in both the X and Y positions. The second is that there is a constant bias predominantly in the X position estimate, but also a small constant bias in the Y position estimate. The constant bias problem is addressed by using the base station as a differential pseudorange correction.

The RTKLIB solution for position is presented under the circumstances that differential corrections are performed. That is, the u-blox data of the rover and the base station are used to compute a GPS position fix and presented in Figure 17:
Figure 17: Cartesian plot of robot position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Dotted Purple: Commanded path, Green: RTKLIB DGPS Position Estimate.)

A notable observation of Figure 17 is that the constant bias terms in both the x and y Cartesian positions are removed. The position estimates are still noisy.

Finally, RTKLIB is permitted to make use of the carrier phase measurements provided by the u-blox GPS receivers from both the base station and rover. A real-time fixed integer ambiguity solution is acquired and results in Figure 18.
Figure 18: Cartesian plot of robot position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Dotted Purple: Commanded path, Green: RTKLIB RTK Position Estimate.)

Post-Processed Physical State with RTKLIB RTK GPS

In order to conclude that the RTKLIB RTK GPS solution using u-blox GPS receivers is competitive with the Novatel RTK GPS solution, the Physical State Observer settings are modified to disable the Novatel inputs and enable the RTKLIB inputs. That is, all “physical state observer” solutions are based on the RTKLIB RTK GPS solution from this point forward.

The top-down Cartesian view of the robot’s position trail is presented in Figure 19.
Figure 19: Cartesian plot of robot position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Dotted Purple: Commanded path, Green: RTKLIB RTK Position Estimate.)

The X and Y Cartesian components, as a function of time, are presented separately in Figure 20 and Figure 21:

Figure 20: The X (East) component of position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Green: RTKLIB RTK GPS Position)
Figure 21: The Y (Northing) component of position. (Black: Physical State Position, Red: Novatel RTK GPS Position, Green: RTKLIB RTK GPS Position)

In order to measure the quality of the RTKLIB GPS position, the X and Y components of the RTKLIB RTK GPS position estimate are compared with the Novatel RTK GPS position estimate and shown over time. The RMS of this residual over the navigation of one complete cycle of the commanded path is used to benchmark the performance of the RTKLIB RTK GPS position and is presented in Figure 22:

Figure 22: The X and Y residuals shown (in Black and Red respectively) are measured from the RTKLIB RTK GPS position estimate of position to Novatel RTK GPS position estimate.

For this particular set of data, the RMS position error is 6.86 centimeters. The Novatel RMS position error, as reported by the Novatel RTK GPS solution, is 3.86 centimeters.
The speed trajectory for one cycle of navigation of the commanded path is presented in Figure 23:

**Figure 23:** The speed trajectory for one cycle of navigation of the commanded path. (Black: Physical State Speed, Red: Novatel RTK GPS Speed, Purple: Commanded speed, Green: RTKLIB RTK GPS speed.)

In order to measure the quality of the RTKLIB RTK GPS speed estimate, the difference between the RTKLIB RTK GPS speed estimate and the Novatel RTK GPS speed estimate is shown over time. The RMS of this residual over the entire navigation of one complete cycle of the commanded path is used to benchmark the performance of the RTKLIB RTK GPS speed estimate. The speed residual is presented in Figure 24:

**Figure 24:** The speed residual shown (in Black) is measured from the RTKLIB RTK GPS speed estimate to the Novatel RTK GPS speed estimate.

For this particular set of data, the RMS speed error is 9.00 centimeters/second.

The angular rate variable is not sensitive to change in GPS position or GPS speed observations and, as a result, is not presented again.
The heading trajectory for this set of data is presented in Figure 25.

**Figure 25:** The heading trajectory for one cycle of navigation. (Black: Physical State Heading, Red: Novatel RTK GPS Heading, Purple: Heading of closest path segment perpendicular to robot's position, Green: RTKLIB RTK GPS Heading.)

In order to measure the quality of the RTKLIB RTK GPS heading estimate, the difference between the RTKLIB RTK GPS heading and the heading of the closest path element is shown over time. The RMS of this residual is used to benchmark the performance of the RTKLIB RTK GPS heading and is shown in Figure 26.

**Figure 26:** The heading residual shown (in solid black) is measured from the Physical State Observer estimate of heading to the heading of the closest path element. Dotted black shows the standard deviation estimate of the heading term from the Physical State Observer.

For this particular set of data, the RMS heading error is 0.1320 radians.

For this entire set of data, the Novatel RTK GPS solution tracked ten satellites, while the RTKLIB RTK GPS solution tracked eight satellites as presented in Figure 27:
Figure 27: The number of satellites tracked over time. (Red: Novatel RTK GPS number of satellites. Green: RTKLIB RTK GPS number of satellites.)

The RMS position, velocity, and heading errors are all comparable to the Novatel GPS RTK solution as presented earlier in Chapter 5. As a result, the u-blox GPS receivers are a suitable replacement navigation component in the CWRU Cutter autonomous robot lawn mower.
CHAPTER 6: CONCLUSIONS AND FUTURE WORK

The results of the ANB on the CWRU Cutter IV platform are summarized in Table 2:

<table>
<thead>
<tr>
<th>Solution</th>
<th>RMS Position (cm)</th>
<th>RMS Speed (cm/s)</th>
<th>RMS Angular Rate (rad/s)</th>
<th>RMS Heading (rad)</th>
<th>Solution Rate (Hz)</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novatel RTK</td>
<td>3.86</td>
<td>3.71</td>
<td>0.0654</td>
<td>0.0636</td>
<td>10</td>
<td>$18,400</td>
</tr>
<tr>
<td>u-blox RTKLIB RTK</td>
<td>6.86</td>
<td>9</td>
<td>0.0653</td>
<td>0.132</td>
<td>5</td>
<td>$500</td>
</tr>
<tr>
<td>Factor</td>
<td>1.78</td>
<td>2.43</td>
<td>1</td>
<td>2.07</td>
<td>0.5</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 2: Conclusion of results from application of the ANB to CWRU Cutter IV.

A factor 1.78 reduction in position quality is the result of a factor 36 reduction in cost. A 2.43 factor degradation in speed and 2.07 factor degradation in heading are also present as a result of the cost savings.

In conclusion, low-cost u-blox GPS receivers can be utilized with appropriate support electronics in order to yield a position and navigation solution for integration with a commercial autonomous robot lawn mower. This work could be utilized in other commercial systems, especially those where a low-cost alternative for positioning is required.

Future work to further improve and extend the prototyped navigation system includes:

- Proper loosely coupled integration of the 6-DOF IMU and wheel speed data complete with bias and drift estimation.
- Proper tightly coupled integration of the 6-DOF IMU and wheel speed data complete with bias and drift estimation in the RTKLIB library.
- Antenna characterization.
• Characterization of the RTKLIB RTK GPS solution in the cases of multipath, signal outages, and signal obstructions.

• Galileo, GLONASS, and/or GPS L5 range integration.
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