Autonomous Utility Mower

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ABSTRACT

Two off-the-shelf John Deere utility mowers were modified for X-by-wire control for the purposes of constructing autonomous vehicles usable in sports-turf mowing applications. The purpose of these mules was to enable the gathering of requirements and customer feedback on such a system. The environment selected initially was that of a baseball stadium. These areas can be characterized as flat, highly controlled and well-groomed, for which precise mowing patterns are necessities.

Typically the operators of these mowers are highly skilled; an autonomous system has the benefits of saving time and labor, permitting the efficient usage of less-skilled employees, and allowing skilled personnel to focus on more complex tasks (such as infield mowing and warning track grooming).

For this application, there are stringent requirements on navigation, path planning and path tracking, while the safeguarding requirements are challenging, but more relaxed than, say, the requirements for golf courses. The calculation of precise position and orientation in this environment requires sensor fusion and is complicated by the fact that frequently the operating area is surrounded by very high walls, limiting sky visibility and preventing the usage of GPS-centric navigation systems. Furthermore, it was desirable to mature the design far enough so that it could be operated regularly by non-technical operators. These results were achieved by developing an accurate local positioning system, making the hardware and software subsystems robust against unexpected failures and constructing a very simple graphical user interface.

This paper will review other relevant existing systems, describe the hardware and software systems utilized, and conclude with descriptions on the performance, customer learning, and description of properties of autonomous systems that enable their integration into a worksite.

Keywords: Mowing, robotic, stadium, turf

1. INTRODUCTION

This paper describes a project to fully automate a utility mower for a sports-turf application. The target environment selected is that of a professional baseball stadium. The primary goal for this project is to learn about the durability, performance and value of autonomous systems in real use environments as a means of progressing towards a commercial autonomous machine that meets customer needs and application requirements. Potential customer benefits include saving time and labor, permitting the efficient use of less-skilled employees, and allowing skilled personnel to focus on more complex tasks (such as infield mowing and warning track grooming). As researchers, the benefits of choosing the baseball stadium environment are that they are typically characterized by flat, hard terrain and highly controlled. While the performance requirements are still quite challenging, the aforementioned qualities tend relax them considerably as compared to, say, mowing a public golf course. The overall intent is that this system represents the first generation of a family of autonomous machines with increasing capability and performance levels.

In recent times, several autonomous consumer mowers have begun to appear on the market from manufacturers including Friendly Robotics, Toro, Husqvarna, Ambrogio, Zucchetti, Electrolux, and Belrobotics. None of these machines is near capable of meeting the requirements of a sports-turf application. There has also been a significant amount of research from academia in the area of autonomous mowing, including Carnegie Melon University (Batavia et. al., 2002; Roth and Batavia, 2002) and the University of Florida (Chandler et al., 2000). Also, the Institute of Navigation has been sponsoring a mowing contest for the past two years and this has stirred greater academic interest in the problem domain.

More recently, the companies Self-Guided Systems LLC, Michigan, USA and McMurtry Ltd., Gloucestershire, UK have advertised commercial mowers tailored toward the same application space discussed here. The efforts of these two companies in particular are notable since they have attempted to address the issues of highly accurate, precise mowing patterns in areas with sky obstruction, where GPS-centric navigation systems typically degrade beyond system tolerances.

First, a brief review of application-specific requirements is given. This is followed by a description of the system hardware and software. Next, a summary of actual performance is presented and then a review of customer learning accomplished during a season of use by two customers. Finally, the conclusion section ends the paper and discusses future work.

2. STADIUM MOWING

Stadium mowing is considered an art work and generally requires a group of highly skilled groundskeepers working together. While the stadium infield and side line area are usually mowed using a walk-behind mower, the outfield mowing is done using a spinning reel mower, such as the John Deere 2653A (fig. 1).

Figure 1. John Deere 2653A utility mower.

Outfield mowing patterns come in many varieties, but a common feature is that they are constructed by driving straight lines to produce the desired striping effect (fig. 2). It is imperative that the mowing stripes have uniform width in order to provide a nice look. The striping itself is caused by the blades of grass being pushed in opposing directions and necessitates that adjacent swaths are mowed in opposite directions. Excessive overlap or any gaps between adjacent stripes, and oscillations or other irregularities while driving can ruin the appearance of the field. It was estimated that the composite error in navigation and control (path tracking) needs to stay below 5 cm during mowing in order to produce acceptable results. Cursory evaluation has shown that expert operators of these machines at normal operating speeds achieve this accuracy.

The outfield mowing task can itself take several hours depending on the desired pattern and may involve more than one mower operating simultaneously. When two mowers operate concurrently, generally they will be mowing in different directions to produce checkered patterns. In general, each stadium may have different sets of mowing patterns they utilize. Throughout the season, the mowing patterns on the field will change. One reason to change mowing patterns is to prevent excessive turf wear.

The checkered mowing pattern in figure 2 is produced by mowing the field in the direction from home plate to center field, and also mowing in the direction from foul pole to foul pole. This picture was taken after a day of testing. During this test, the mower was not actually cutting the grass, the reels were lowered while making the passes but were not spinning; the visible striping effect was produced from the rollers on the front of the reels.

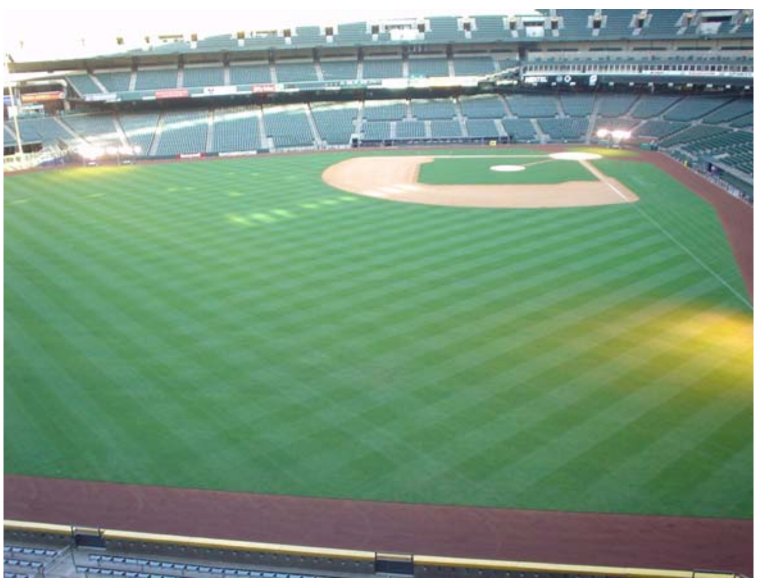

Figure 2. Chase Field, Phoenix, Az.

Normal mowing operating speed is around 1.5 - 2.5 m/s. At low speeds or when the mower is stationary, the reels are raised to prevent damage to the turf. The reels are also raised any time the vehicle leaves the grass area. Excessive turning on the outfield grass is also frowned upon.

In many cases, the groundskeepers will empty the clippings from the baskets during operation as opposed to letting them fall to the surface. Depending on the length of the grass, this emptying can occur as often as once per pass across the field. This additional task can greatly increase the operation time and either requires coordination with an additional vehicle used to store and haul the clippings or driving the mower itself to a container off the field somewhere.

Particularly on the day of a baseball game, there are many tasks beyond the outfield mowing that must be performed, such as raking and infield mowing. Another motivation for making the mower autonomous is to free the workers to do these other tasks.

3. CONCEPT OF OPERATION

The current prototype systems are installed by first mounting fixed navigation beacons around the stadium. Next, the field boundaries are surveyed using the navigation system and are input into a map file. The map, together with each set of pattern preferences, is used to create the respective mission plan using an engineering user interface. An example mission plan is shown graphically in figure 3. With this current design, autonomously mowing a checkered pattern requires two separate operations, one for each direction.

The system is intended to be used in the field by a non-technical operator. As such, it was necessary to not only execute the desired mowing patterns and meet the performance requirements mentioned above, but also provide a simple and intuitive, small, handheld user interface with wireless connectivity to the vehicle.

Figure 3. Foul pole to foul pole pattern.

The following steps are performed by the operator to execute the autonomous mowing feature:

1. Inspects and adjusts machine (mowing height, reel to bedknife, fluid levels, etc.).
2. Visually inspects mowing area and removes potential obstacles (debris, stuck irrigation heads, etc.).
3. Starts onboard computer system.
4. Starts machine and manually drives onto field.
5. Turns on user interface, ensures proper connection to system and system initialization.
6. Selects pre-computed desired mowing pattern from menu on user interface (fig. 4).

7. Vehicle begins operation. Operator monitors progress during operation visually and from the user interface, and remains in view of vehicle. Operator has capability of pausing operation at any time (to empty clippings, for example) or exercising remote emergency stop, if necessary (hopefully never).
8. System notifies the operator when the mowing pattern is complete. Operator powers off computer and user interface, or alternatively can select another mowing pattern to execute.

Figure 4. Screenshot of user interface.

The system is described in more detail in the next section.

4. SYSTEM DESCRIPTION

4.1 Architecture

Most of the software is written using a Model Driven Development tool in C++. The system architecture is such that it can easily be adapted to changes in hardware, technology, and application (fig. 5). The same software base has been used successfully on several projects already, with various processors and operating systems, and combinations of sensors and algorithms, vehicles and applications.

There are five major components that comprise the system: vehicle control unit (VCU), navigation, perception, intelligent vehicle controller (IVC), and user interface. In figure 5, “Robot (Vehicle) Controller” refers to IVC. In this application, all five major components reside on separate processors, but in other instances some of the core components reside on the same physical processing unit. In the following, each major component is discussed in more detail.

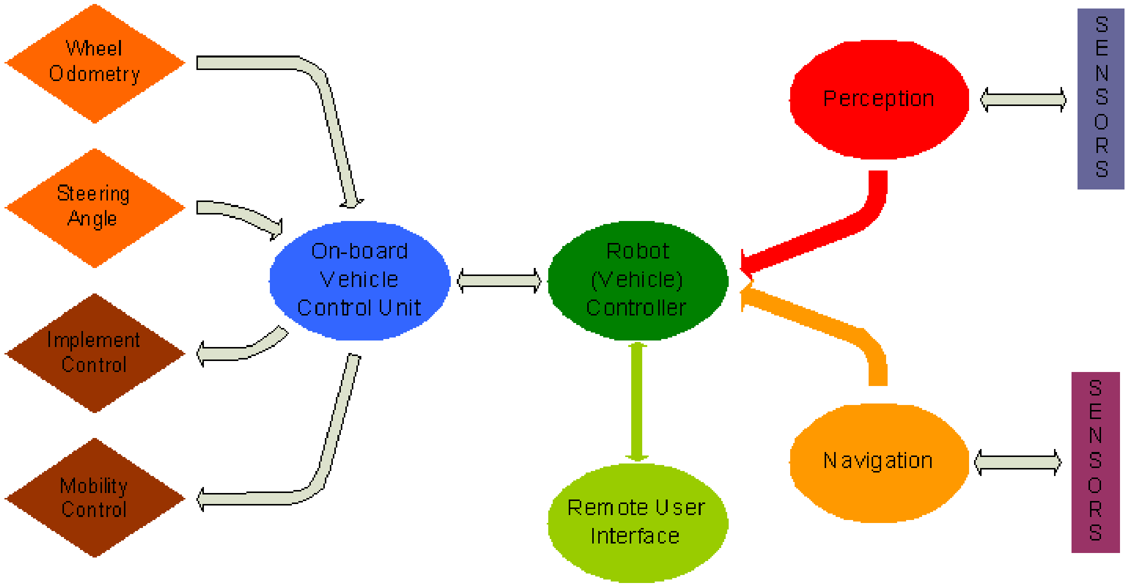

Figure 5. System architecture.

4.2 Vehicle and Vehicle Control Unit (VCU)

The vehicle used in this project is a modified version of the John Deere 2653A (fig. 6). The RF ranging antenna is at the top of the mast in the front of the vehicle. At the base of the mast is a SICK™ laser used by the perception component, as well as two boxes that house the perception and navigation subsystem computers. The third box just below the facing side of the seat houses the computer with the intelligent vehicle controller. The vehicle control unit is underneath and is not visible in figure 6.

Figure 6. Modified X-by-Wire John Deere 2653A.

Specifically, the vehicle was converted to X-by-Wire control by creating a VCU with a CAN messaging interface to enable control by an external processor. The low-level control algorithms (closed-loop steering and velocity, implement control) were implemented inside the VCU. Command and feedback signals between the VCU and the IVC enabled autonomous operation. At the same time, it is possible to use this machine manually, so that groundskeepers could alternatively use the vehicle as they do the off-the-shelf version of the vehicle available today.

4.3 Navigation

The use of GPS requires good sky visibility. In this application, due to the stringent navigation accuracy requirements, an RTK-GPS solution is required, which requires the use of a base station. Because many of the baseball stadiums have high walls and other obstructions around the field, RTK-GPS is inadequate, even with augmentation by (affordable) inertial sensors and/or odometry sensors. This necessitated the use of alternative technology.

Other earlier prototype systems featured local positioning systems (LPS) based on ultrasonic ranging, using time-of-flight measurements from a vehicle to a set of beacons at fixed locations in the environment (Hunt et al., 2006; Zeitzew, 2004). This positioning system had insufficient range to support sports-turf areas, which can involve 100 meter ranges, or more. As a result, a new LPS based on radiofrequency signals was recently developed, which exceed the required range and accuracy requirements. The LPS system requires an antenna on the vehicle and involves RF ranging to battery-operated beacons, typically 6 in this application, mounted on the walls around the stadium. The LPS is part of a larger sensor fusion component that incorporates these ranges together with vehicle odometry information and measurements from inertial sensors (3-axis gyroscope and accelerometers) into an Extended Kalman Filter. The testing shows that the error due to the navigation system is on the order of 2 cm RMS (root mean squared) at normal operating speeds. Moreover, studies indicate that our LPS system has a range of hundreds of meters and can be mass-produced in a cost-effective manner for future products.

Finally, note that the sensor fusion component also admits GPS (or RTK-GPS) instead of or in addition to the LPS; the navigation system was built flexibility to easily allow investigation of different combinations of sensors.

4.4 Perception

Part of the perception research included the investigation of various types of sensors, including ultrasonic, radar and laser, and the usage of differing safeguarding algorithms. Generally, the byproduct of the perception system can be used by other elements for application-specific purposes. In the present case, the only usage of the perception data was to enable vehicle safeguarding.

Because the highest priority in this application is to maintain precise mowing patterns, this alleviated the need to deploy what can generally be a quite complicated obstacle avoidance system. Here, the only acceptable response to obstacles during mowing is to either reduce vehicle speed or stop. Furthermore, since the implementation did not include reverse operation, it allowed deploying a greatly simplified safeguarding system onto the fielded system. Specifically, the algorithm relied only on the range scans from a SICK™ laser mounted on the front of the vehicle (fig. 6). The range scans were combined with vehicle feedback data in order to determine if the current trajectory was clear; if not, the vehicle would reduce its speed as a function of the distance to the nearest obstruction, eventually stopping if necessary.

While this system proved to be reliable and robust against safeguarding humans, walls and other large obstacles, its high cost and inability to detect people approaching the machine from the sides or rear indicate that more work is necessary to provide a comprehensive and marketable safeguarding system.

4.5 Intelligent Vehicle Controller (IVC)

The IVC has several responsibilities within the system, including:

- Mission Planning: Ability to construct mission plans based on environment maps and tunable parameters, as well as providing planning services during mission execution. This includes area coverage path planning (Gray, 2006).
- Mission Execution: Includes application-specific elements that run during the mission. One such example is the path tracker; the responsibility of the path tracker is to compute steering and velocity commands so that the vehicle follows the desired path. The path tracking algorithm utilized in this project was a standard PID with feed-forward term to account for path curvature, using the computed path lateral deviation as the error signal.
- User Interface: Gateway to send and receive data from user interface(s).
- VCU Interface: Gateway to the vehicle's actuators and sensors.

4.6 User Interface

Two user interfaces were constructed for this project. The first is best characterized as an engineering user interface, which provided administrative-level access to the functionality of the system. The second user interface was a simplified version that provided only the functionality that was deemed to be useful, usable and desirable. The later user interface ran on a small Pocket PC device as shown in figure 7.

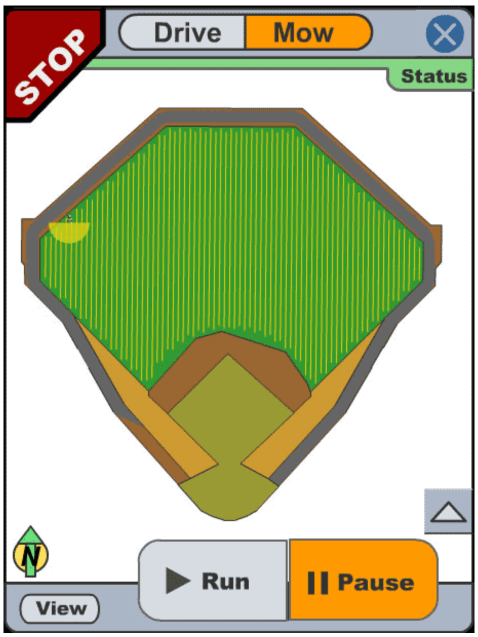

Figure 7. Screenshot of operator user interface during mowing operation.

The mower icon is on left side and shown with a notional hemisphere of coverage by the perception system. Via this user interface, the operator is allowed to:

- Select from available maps.
- Select from available missions for the selected map.
- Start, stop and pause missions.
- Monitor progress graphically and other simple feedback signals.
- Teleoperate the vehicle if necessary.

5. PERFORMANCE

5.1 Operating in Stadiums

Two such vehicles were fielded into professional baseball stadiums, one major league and one minor league. Both of these systems were utilized over the course of several weeks during the spring 2005 baseball season. During the latter portion of the season, the systems were used by the regular groundskeepers whereas the engineering role migrated to that of occasional observation. The systems were frequently operated solely by the groundskeepers. The groundskeepers were asked to log their comments, and these were collected and later analyzed, the results of which are discussed below in the section on customer learning. A third system was used for local testing at a large athletic facility over several fields (mostly soccer fields).

5.2 Path Tracking

Table 1 summarizes typical RMS path tracking performance. Transport corresponds to periods where the implement (spinning reels) are disengaged, like during turns between rows. The numbers were computed by averaging the RMS errors computed over several missions and the two stadiums. It shows that the system was able to meet the required subsystem specifications. Note that the total system error is comprised of both the path tracking (how well vehicle tracks reference) and navigation system (how well reference matches ground truth) errors. The latter is not reflected by these numbers and was validated by other means.

Table 1. Average RMS error for mowing and transport autonomous operation.

Parameter	Initial Specification	Current Performance
Mowing (1.6 m/s)	3.5 cm	2.1 cm
Transport (2.3 m/s)	9.0 cm	3.9 cm

6. CUSTOMER LEARNING

The positive feedback from the customers included appreciation for the straightness of mowing stripes and the time savings that allowed employees to focus on other tasks, particularly during baseball team home stands during which the outfield is mowed every day. Having the autonomous machine in regular operation would allow a reduction in the need for highly skilled drivers and potentially allow completion of the required work with a smaller staff.

Other observations made include:

- The assumptions that operators will be comfortable being a full-time safety rider or that when off-board will give full attention to the machine during autonomous operation are erroneous. Very quickly they become comfortable with the autonomous machine and will ignore it, spending time raking the warning track, painting a logo or other activity, often with their backs toward the machine.
- The need to empty the clippings in some stadiums, and the performance of peripheral tasks such as line painting, present an engineering challenge to further expand the scope stadium automation.
- There would be value in having two (or more) autonomous machines operating simultaneously in order to provide even more time and labor savings, considering that checkered mowing patterns are prevalent in the industry.
- The area bordering the outfield is often cluttered with workers or other equipment. Further progress is needed to safeguard robustly against these hazards.
- The perception system should be upgraded to account for smaller and moving obstacles typically found in the operating environment.
- The ability to detect stuck irrigation heads that fail to retract below surface, which can cause damage to the spinning reels, would also be of value.
- In some cases, a small part of the field is damaged or particularly sensitive and the groundskeeper wishes to avoid mowing or driving over it. The ability to easily adjust the planned mowing pattern from the handheld user interface would be valued.
- The ability to drive in reverse and utilize 3-point turns at the end of rows, rather than always driving forward and turning outside the field, has operational benefit.
- It is worth revisiting the user interface design and form factor, perhaps migrating to a smaller and even simpler design.
- The system also featured the ability to teleoperate the vehicle, but it turned out to not be sufficiently interesting or useful to anyone other than the engineers who worked on the project.

7. CONCLUSION

This paper has described the deployment of two off-the-shelf John Deere utility mowers that were modified for X-by-Wire control for the purposes of constructing autonomous vehicles usable in sports-turf applications.

It has had two main benefits, first in providing a mechanism for increasing the company’s expertise in autonomous vehicle systems generally and in sports-turf applications in particular and secondly in gaining understanding of the value of such systems to customers. An improvement of the robustness of the vehicle, hardware and software, incrementally improving upon it, and also explore other application spaces will be continued.

In parallel, a realistic business model for this type of equipment needs to be built.

8. ACKNOWLEDGEMENTS

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