M.L. 2018 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Agricultural Weed Control Using Autonomous Mowers
PROJECT MANAGER: Eric Buchanan
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08d as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

APPROPRIATION AMOUNT: $750,000
AMOUNT SPENT: $699,793
AMOUNT REMAINING: $50,207

Sound bite of Project Outcomes and Results
An autonomous electric mower, along with a solar powered charging trailer, was successfully developed and demonstrated to control weeds in cow pastures. The "Cowbot" eliminates the need for pesticides in conventional pastures and provides a carbon-free solution for organic pastures.

Overall Project Outcome and Results
Minnesota farmers and land managers are engaged in an annual battle to control weeds. Each year, significant amounts of herbicide, diesel fuel, labor, and money are expended to stay ahead of weed infestations. Our project team developed an autonomous mowing robot, we call Cowbot, that can design a path to mow a pasture given the GPS coordinates of the pasture corners. The Cowbot can then accurately follow this path and return to its starting point when mowing is completed. A specially designed solar charging trailer is placed at the starting point to recharge the Cowbot when its batteries are low. Widespread adoption of the technology we demonstrated could lead to:

- Significant reductions in the use of herbicides on agricultural and natural lands,
- Replacement of fossil fuel with clean energy produced locally,
- Protection of water resources by preventing surface and ground water contamination with herbicides,
- Reducing the impact of herbicide on wildlife, desired native plant species, and the evolution of herbicide tolerant 'super' weeds,

The project team consisted of researchers at the University of Minnesota from several departments working together to develop a robotic pasture mower in partnership with a Minnesota manufacturing company, The Toro Company. Safety protocols were developed for field testing and safety implications of autonomous farm vehicles in general were researched. The Cowbot was field tested in pastures at the U of MN West Central Research and Outreach Center (WCROC) comparing its performance to a conventional mower deck pulled by a diesel tractor. The Cowbot successfully mowed three, two-acre pasture paddocks demonstrating three different path strategies. It returned to the charging trailer after mowing each paddock and was successfully recharged. A dairy producer reviewed the mowed pasture and judged the Cowbot mowed paddocks to offer equivalent or better control of weeds than the tractor mowed paddocks.

Project Results Use and Dissemination
Several academic papers were published relating to technology used to design mowing paths and control the Cowbot. The Cowbot was demonstrated to farmers and land managers at several events like the Midwest Farm Energy Conference at the WCROC in 2019 and 2022. It was also featured in an episode of the PBS television

show “The Prairie Sportsman” along with interviews with several project team members airing in March 2021. The Cowbot was a featured live demonstration at a state-wide expo in August 2021 called FarmFest. Finally, the Cowbot appeared in several print media articles including the Star Tribune and AgWeek.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2018 LCCMR Work Plan Final Report

Date of Submission: August 18, 2022

Final Report

Date of Work Plan Approval: June 27, 2018

Project Completion Date: June 30, 2022

PROJECT TITLE: Agricultural Weed Control Using Autonomous Mowers

Project Manager: Eric Buchanan

Organization: Regents of the University of Minnesota

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Location: Statewide

Total ENRTF Project Budget:

ENRTF Appropriation:	**$750,000**
Amount Spent:	**$699,793**
Balance:	**$ 50,207**

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08d as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

Appropriation Language: $750,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for the West Central Research and Outreach Center at Morris to design, integrate, and field-test new technology mowers to control weeds, reduce herbicide use, reduce energy costs, and improve native vegetation and forage quality on agricultural lands. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.

M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2022]

I. PROJECT TITLE: LCCMR 157E "Agricultural Weed Control Using Autonomous Mowers"

II. PROJECT STATEMENT:

Minnesota farmers and land managers are engaged in an annual battle to control weeds. Each year, significant amounts of herbicide, diesel fuel, labor, and money are expended in an effort to stay ahead of weed infestations. Control of weeds is critical in the production of food. Current methods of weed control using herbicides have been very effective, but may have unintentional and harmful consequences to our air, land, water, and wildlife resources. We propose to develop improved methods using robots to control weeds on agricultural lands. Solar energy will be used to power the robots. In this first phase, weed control robots will be tested within pastures. In a future phase, testing will include weeding robots within row crops such as corn and soybeans. In accomplishing these goals, we aspire to:

- Significantly reduce the use of herbicides on agricultural and natural lands across the State of Minnesota,
- Replace fossil fuel and resulting air emissions with clean energy produced locally,
- Protect water resources by preventing surface and ground water contamination with herbicides,
- Reduce the impact of herbicide on wildlife, desired native plant species, and the evolution of herbicide tolerant 'super' weeds,
- Develop new time-saving tools for farmers as well as natural lands managers to control weeds,
- Advance the rapidly growing field of robotics within the State,
- Partner with MN companies to development and manufacture cutting-edge robotic technologies.

The project team will develop and test a robotic mowing system to control weeds and improve forage quality in a dairy pasture. An electric powered robot will be recharged by a portable solar PV charging station that will be installed on a cargo trailer. The robotic pasture mower will be developed in partnership with a Minnesota manufacturing company, The Toro Company, and researchers at U of MN. Safety protocols will be developed and tested. The mowing robot will then be field tested in pastures at the U of MN West Central Research and Outreach Center (WCROC). Finally, the robot will be demonstrated to farmers and land managers at workshops, field days, and events such as Farmfest. Additional funding will be sought in a future second phase and will include field robots for weed control in corn and soybean fields. The second phase inter-row and intra-row weed hunter robots will be more technically advanced requiring additional engineering, navigation and visual identification hardware and software development, and testing.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 1, 2019:

The project is still in the initial stage, but is on schedule. A contract has been executed with TORO for development of an electric mower and integration of autonomous control equipment. TORO has converted a diesel-powered lawn mower to electric power and is proceeding with installation of a modified flail mower which will work better in a pasture application than a traditional deck mower. Operation of the electric powered mower has been demonstrated to the project team at TORO headquarters and on the planned test site at the WCROC in Morris, MN.

Robotic control algorithm development has focused on ways to map an area, like a pasture, and determine a path to fully cover that area. Additional work has been completed investigating ways to get a robot to follow that path – called trajectory following. Initial testing has been completed with a commercially available small robot following trajectories on the St. Paul campus with the aid of a GPS receiver.

Mower charging specifications are being finalized to facilitate design of the cargo trailer solar charging system. Likewise, row crop weeding implement specifications are being developed so implements can be built this winter and tested in the spring. There are no specific safety standards for autonomous ride on mowers; however, safety concerns will be addressed using multiple existing standards.

Project Status as of July 1, 2019:
Progress continues on developing an autonomous mower. TORO has added a prototype flail mower to the converted diesel mower and it has been tested in a pasture at the WCROC. Programming and sensor development continues at TORO headquarters. A solar panel/battery system has been purchased and delivered to the WCROC for conversion of a cargo trailer into a solar charging station for the mower.

Project Status as of January 1, 2020:
An autonomous pasture mower, "Cowbot", has been tested successfully three times in a pasture at the WCROC in addition to many preliminary tests at the Toro facility in Bloomington. The mower has proven its ability to navigate and mow in very rough pasture conditions. Toro will be improving some of the mechanical and electrical systems over the winter while the programming group refines their control programming.

Conversion of a cargo trailer into a mobile solar charging station for the Cowbot continued with the design of a solar panel mounting system to get ten panels on the trailer. Two row crop weeding implements were tested in field-like conditions at the WCROC pulled by the Cowbot.

Amendment Request as of March 5, 2020
Activity 3 covers effort to develop weed control implement to pull through early stage row crops with an autonomous electric vehicle. The vehicle was planned to be similar to an electric Polaris Ranger that would be modified to be controlled autonomously. The project team believes the already modified Toro mower can be used to pull the weed control implement avoiding the risk of trying to modify and control a new vehicle. A field test was conducted with a human driver to confirm the Cowbot is capable of pulling the prototype implements and vehicle control of the Cowbot has already been established.

This amendment does not change the overall budget or the portion allocated to Activity 3, but would shift funds budgeted for purchasing a new electric vehicle to labor and equipment to modify and program the Cowbot for Activity 3 tasks.
Amendment Approved by LCCMR 4/28/2020

Project Status as of July 1, 2020:
Several modifications have been made to the Cowbot vehicle and its programming over the winter to improve its performance. These modifications will be tested in cow pastures at the WCROC this summer after delays due to COVID19 prevented spring testing. The cargo trailer charging station has been completed and commissioned.

Project Status as of January 1, 2021:
Delays to the start of pasture testing resulted from a University shutdown due to the COVID pandemic. Moreover, new approval procedures were developed at the University and Toro to allow work to continue on site and to allow off-site personnel access. Pasture testing was conducted in late September and early November. Overall, pasture testing in the 2020 season was very successful. Cowbot performance was improved with better path following and turning abilities, additional sensors were installed and used to collect important data for future code development, and pasture performance from previous testing was replicated providing some confidence in the methodology and equipment. A solar charging trailer was deployed in the pasture and was able to charge the Cowbot on site. The charging trailer worked as expected and is fully operational.

Project extended to June 30, 2022 by LCCMR 6/30/21 as a result of M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18, legislative extension criteria being met.

Project Status as of June 30, 2021:
Several Modifications were made to the Cowbot over the winter at Toro. These included fixing some software bugs in the machine control code and performing minor mower maintenance. Also, several modifications to the University's path planning and navigation code were made and tested at Toro by University personnel. Successful pasture testing was conducted at the WCROC during the last week of June. Preparations are being made to demonstrate the Cowbot at Farm Fest in August 2021.

Amendment Request as of June 30, 2021
Farmfest booth fees and expenses are higher than expected so this amendment requests transferring unspent funds from another category to the Farmfest exhibitor category. Specifically, $3214 are being reduced in the budget for an electrician to wire a solar charging trailer and added to the Farmfest exhibitor budget raising it from $2400 to $5614. Also, in-state travel expenses for several different departments are being combined into a single budget line to simplify reporting. There is no change to the total budget for travel.

Amendment Approved by LCCMR 9/7/2021

Project Status as of January 31, 2022:
The Cowbot was a featured item at Farm Fest in August of 2021. A large booth area was secured and the Cowbot was used in two live demonstrations each of the three days of the show.

Final testing of the Cowbot was completed in October 2021. A 12-acre pasture was partitioned into six paddocks three of which were mowed by the Cowbot and three were mowed by a traditional tractor pulled mower. Mowing time, energy use, and weed control were recorded for both mowing methods. The solar charging trailer was successfully used to charge the Cowbot between mowing sessions.

Amendment Request as of March 7, 2022

We are requesting funds be transferred from the FarmFest Exhibitor Fee and Computer Services Fee budgets to the Travel budget:

- FarmFest Fee budget would be reduced by $1,450 to a revised budget of $4,164
- Computer Service Fee budget would be reduced by $1,500 to a revised budget of $18,081
- The travel budget would be increased by $2,950 to a revised budget of $15,045

These changes are necessary because travel expenses were more than expected due to changes in the University's travel policies due to COVID. For instance, researchers traveling the Minneapolis had to drive in separate vehicles. We also expect additional travel expenses related to demonstrating Cowbot at the Midwest Farm Energy Conference held in Morris in June 2022.

We are also requesting funds be transferred from the Equipment/Tools budget (specifically materials to fabricate custom implements) to the Capital budget (specifically solar PV system):

- Materials to fabricate weeding implements budget would be reduced by $15,372 to a revised budget of $2,628
- Solar PV system budget would be increased by $15,372 to a revised budget of $28,972

This change is needed to increase the storage capacity of the charging trailer to better match the needs of the Cowbot mower and to decrease the weight of the trailer by using lighter lithium-ion batteries. The excessive weight in the front of the trailer has made using the trailer problematic.

No changes to the total project budget are requested.

We are also requesting to extend the dates of Activity 1 Outcomes 5 & 6 and Activity 3 Outcomes 6 &7 to align with the end date of the project.

Amendment Approved by LCCMR 3/30/2022

Final Update June 30, 2022

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IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1:

Description: Design, Integrate, and Field Test an Autonomous Pasture Mower

A robotic mower capable of operating in harsh pasture terrains will be jointly developed by the U of MN and a
Minnesota turf equipment manufacturer, The Toro Company (Toro). A diesel Groundsmaster^{TM} mower will be provided by Toro as an in-kind contribution. Toro will convert the mower from diesel to electric power by removing the diesel engine and fuel tank, then an electric motor and battery pack capable of powering the mower will be installed. A 100V Lithium battery pack (2 x 14.4 kWh) along with a high efficiency PMAC electric motor is anticipated to be used to power the mower. The Parker liquid cooled Permanent Magnet Alternating Current (aka. brushless) motor is manufactured in New Ulm, MN. The mower will be converted to an autonomous ready state with electronic control enabled to start, shutoff, steer, engage / disengage mower, change of operating speed, implement lift, and change of direction (FWD/REV). Toro will also develop and incorporate control parameters that will prevent the mower to be operated outside of normal /safe operating parameters. These control parameters will include operating speed, cornering speed, engagement of mower, and motor RPMs. Toro will acquire and install a rough mower attachment which the project team believes will be best suited for pasture mowing.

As Toro is modifying the Groundsmaster^{TM} mower, researchers in the U of MN Department of Computer Science and Engineering will purchase and assemble instruments and components for the mower to operate autonomously. A GPS-based system will be developed which will allow the mower to navigate through the pasture using pre-determined GPS points. A LiDAR system will be utilized for hazard detection and avoidance and to signal when necessary to shut down the mower. A laptop computer will be purchased for which control logic will be programmed into the hardware for the mower to operate autonomously. The control logic will include energy awareness planning. Energy awareness planning allows for the efficient use of energy in planning routes traveled by the robot. Simultaneously, researchers in the U of MN Department of Bioproducts and Biosystems Engineering will consult with Toro and Computer Science researchers in the overall development. In addition, the researchers will serve in an important capacity in conducting a Hazardous Operability study (HazOP) which essentially addresses all the “what if?” scenarios and assists in risk reduction. The project team will review the design and integration of the mower identifying potential hazards (including but not limited to mechanical failure, obstacles, and wildlife and/or human interactions), designing control systems to mitigate hazards, and incorporate redundant controls in case one or more systems fail. The system will be designed and constructed to “fail safe”.

Toro and the U of MN researchers will work together to integrate the autonomous operation hardware and software into the modified Groundsmaster^{TM} mower. Once completed, the mower will be commissioned at The Toro Company Headquarters in Bloomington, MN and/or their local field test site in Farmington, MN. Commissioning will include a series of operational tests for basic operation as well as HazOp / fail safe verification. Once the autonomous mower has been commissioned and certified operational by the research team, the mower will be transported to the U of MN West Central Research and Outreach Center (WCROC) near Morris, MN for field-testing in a dairy pasture.

The WCROC utilizes several pastures in a Management Intensive Grazing (MIG) system at its research farm. Approximately 250 cows are pastured at the WCROC and are milked twice per day. Each time the cows are milked, they are moved into a fresh paddock allowing access to new forage. Since half the dairy is organic, weeds within the pasture cannot be sprayed. Mowing is then required to control weeds and also to improve forage quality. As the cows graze, they selectively pick the lushest forage leaving mature grass and forbs as well as weeds. The weeds then tend to flourish and takeover a pasture. So as the cows finish grazing a pasture and move on to the next, the traditional practice is to mow the grazed pasture with a tractor and flail mower. This process is energy intensive and time consuming. The WCROC is working to reduce the fossil energy consumption and the carbon footprint of dairy production. Combined with the certified organic requirements, limited tools are available for effective weed control in pastures without using diesel-powered equipment. In addition, dairy farms in general do not have available labor to continuously mow pastures. Therefore, a battery powered robot coupled with a solar powered charging station, may be viable.

Beginning in the spring of 2020, the robotic mower will be put through a series of initial operational tests and then will move into field tests. Initial testing will include line following, obstacle detection, and pasture coverage with integrated obstacle avoidance. For the field tests, a 10 to 15 acre pasture will be utilized. The pasture will consist of a cool season grass mixture consistent with conventional Minnesota pastures. The pasture will be divided into 3 blocks each consisting of two treatments. The first treatment will be a control utilizing a tractor and flail mower driven by a WCROC employee. The second treatment will be the robotic mower. After the dairy cows graze through the pasture, the tractor will mow three replicated blocks and the robotic mower will also mow three replicated blocks. Variables will be measured such as time required to complete mowing, energy consumed, length and quality of cut, effectiveness of weed control (plant counts in randomly placed squares), hours of labor required, maintenance / repairs required, and navigation / hazardous issues encountered. Refinements will be made to the robotic mower throughout the test period. Testing will continue throughout the grazing season (generally May through September). Each time the dairy cows are rotated through, the experiment will be repeated.

The robotic mower will be demonstrated to farmers and other land managers during several tours, field days, and workshops at the WCROC and potentially at other locations within the State. Finally, the robotic mower will be displayed at FarmFest near Redwood Falls, MN in August 2020. Farmfest is one of the largest farm industry events in the Midwest and thousands of farmers attend each year.

Following the initial grazing / mowing season in 2020, refinements will be made by the project team and final field testing will be completed in spring / Early Summer 2021. Field test data will be analyzed and a final report issued on or before August 15, 2021.

Summary Budget Information for Activity 1:

ENRTF Budget:	**$ 357,060**
Amount Spent:	**$ 357,060**
Balance:	**$ 0**

Outcome	Completion Date
1. Convert Toro Groundsmaster Mower from diesel to electric power	*5/1/2019*
2. Develop navigation / logic systems to allow for autonomous operation	*7/2/2019*
3. Develop and test safety and fail-safe logic and protocols	*10/1/2019*
4. Integrate and commission mower with navigation systems and conduct HazOP	*4/1/2020*
5. Field test robot within pastures at the WCROC	*6/1/2022*
6. Display / demonstrate the mowing robot at state-wide events	*6/30/2022*

Activity 1 Status as of January 1, 2019:
Toro has completed the 1st Phase electric conversion of a GM3280-D mower platform from diesel-engine to battery-electric. This has involved the acquisition of a Toro GroundsMaster 3280-D with 72"rotary mower and most of the electric conversion components (including two 14.4 kWH ZERO 100V lithium battery packs, onboard 1.3 KW charger, Parker GVM liquid cooled 100V motor and controller, electric cooling system, and revised PTO drivetrain components). Necessary metal fabrication was completed in the Toro shop, custom electrical harnesses were designed and sourced for the prototype. The mower was operated in late October, 2018, and demonstrated acceptable performance. A Toro 60" flail mower has been identified for conversion for the pasture application. Design work to retrofit it for the GM3280 mower platform has been completed, and initial installation and field testing is planned for Feb, 2019. Current design activity is focused on robot-ready conversion primarily related to electronic-controlled traction and steering system design and components.

Current work on control algorithms assumes that the pasture is represented as a 2D polygon. The robot is represented as a unit square. The goal is to plan a trajectory for the robot so that every point in the polygon can be visited, and for the robot to follow the planned trajectory. Early performance testing was done by pre-recording a trajectory in a garden on the Saint Paul Campus of the University of Minnesota. Then a commercially available ground robot (Clearpath Husky) was outfitted with a simple PID controller and GPS unit to see if it could follow the planned path. It performed well. This method was also tested in a corn field – a much more challenging environment – and it also performed well there. Future work will incorporate obstacle avoidance and determining energy efficient paths with hilly terrain.

Activity 1 Status as of July 1, 2019:
TORO has completed installation of a modified flail mower and the mower has been tested in a pasture at the WCROC. Early results indicate the mower will be effective at cutting thistles and other weeds left after cows have grazed a pasture. Several test runs were made at different speeds while monitoring energy usage and cutting effectiveness to help determine optimal operating conditions.

TORO has completed modification of the mower steering and traction systems to make them electronically controllable. These systems also performed well, but there are a few bugs that still need to be worked out. A beacon indicting when the mower is in autonomous mode has been added to a canopy on the mower and a remote kill switch has been added to satisfy TORO liability concerns. The switch will be help by a test supervisor for each autonomous run allowing the mower to be shut down should any problems arise.

Activity 1 Status as of January 1, 2020:

Toro made mechanical modifications to the flail mower to increase its mowing height to better meet the needs of pasture management. The goal is to cut weeds soon after cows have grazed, but not to cut any more grass than needed. Other modifications were aimed at improving the stiffness of computer and sensor mounting methods. These modifications were because of the excessively rough terrain in WCROC cow pastures due primarily to gopher mounds. Pasture testing revealed the need for additional Cowbot improvements to be addressed this winter by Toro. These include guards for sensors and oil filters that mount under the mower, larger caster wheels and mounts at the front of the flail mower, and new tires with better traction.

The programming team conducted many tests at Toro's Bloomington facility to establish the ability of the navigation code to send commands to the Cowbot control system. Work then proceeded to develop path planning protocols for mowing. Once a mowing perimeter is established via computer input of coordinates or by a human operator driving along the desired perimeter, a path planning protocol calculates a path for mowing the defined shape. This was done using adjacent paths and turning around at the end of each row, or using an inward spiral path. Testing then moved to an actual pasture at the WCROC to test Cowbot's capabilities in the actual use environment. The programming team made two trips to Morris for pasture testing. On both occasions several trials were completed using different mower parameters (speed, cutting height, etc.) and different programming parameters (path type, turning radius, way point calculation, etc.). For the most part, the mower performed better than expected for initial field trials. Very little optimization was needed to get the mower working autonomously and completely mowing several polygons with both adjacent row and spiral paths. Pasture testing did reveal a few areas where the code could be improved. Refinements that will be made over the winter include better path following accuracy, improved behavior when a way point is missed, and better operation of the flail mower.

Preliminary safety protocols were developed and used for pasture testing. Protocols will continue to be refined and compared with similar industry standards to ensure safe operation in this new field of autonomous farm vehicles.

Activity 1 Status as of July 1, 2020:

Several modifications have been made to the cowbot to improve its performance in pasture mowing and ease of transport. Specifically, the cowbot canopy was too tall to allow the mower to be transported inside the solar charging cargo trailer as initially hoped. Toro modified the canopy structure so that it can be folded down for transport which should allow it to fit inside the trailer. Several sensors and a laptop mount are also attached to the canopy structure and these have been improved to better withstand the vibrations which result from rough pasture conditions. There was an electrical issue with the onboard battery charger which has been resolved. Inertial Measurement Unit (IMU) sensors have been installed which are expected to significantly improve the ability of the cowbot to stay on its path. Other changes allow the mower to operate better (and faster) in reverse which will allow the cowbot to pull weeding implements for activity 3. Navigational programming has also been modified to improve the path following behavior of the cowbot.

Pasture testing was planned to start in late May, but COVID19 restrictions put in place by Toro and the University of Minnesota led to a delay in the plan. A research approval protocol was instituted by the University to allow projects that are time sensitive to proceed in an environment that suspended all other research activity. This project has been approved to proceed, but there were delays in allowing grad students on the twin cities campus to access their lab to transport equipment to Toro for installation on the cowbot. There was also some delay with Toro returning to on-site work and allowing non-employee visitors. Pasture mowing is now planned for mid to late July.

Activity 1 Status as of January 1, 2021:
During the last test run of 2019 there was a failure of the flail mower. Inspection revealed a broken belt tensioning pulley. This was repaired and pasture testing was conducted during the week of September 21, 2020 after several delays due to COVID restrictions. Toro personnel planned to install an upgrade to the cowbot vehicle code that should improve steering response, but found some problems affecting the onboard display. These were resolved, but a team decision was made to test with the base vehicle code without the new steering table to ensure data consistency with previous testing. The upgraded code will be installed and checked out this winter when the cowbot is returned to Toro.

The Prairie Sportsman, a local PBS show also funded by the LCCMR, came out on Monday (9/21) and interviewed the project team. They returned on Wednesday to film the Cowbot in action and are planning to air a segment about the cowbot in May 2021.

New sensors (Lidar, new IMU, and onboard camera) were mounted on the cowbot and were used to collect data for analysis and continued code development over the winter. A drone and camera were also used record the test pasture before and after mowing. This is also intended to aid code development and future improvements that might include assessing weed coverage prior to mowing and developing a mower path customized to actual pasture conditions.

Unusually good weather allowed an additional pasture test session during the first week of November. This test was used to replicate previous results and collect more sensor data for code development. Overall, pasture testing in the 2020 season was very successful. Cowbot performance was improved with better path following and turning abilities, additional sensors were installed and used to collect important data for future code development, and pasture performance from previous testing was replicated providing some confidence in the methodology and equipment.

Activity 1 Status as of June 30, 2021:
Several improvements were made to the Cowbot machine code that should allow better control and steering accuracy. Additional instructions were added to allow the University navigation code to control engine speed while in autonomous mode. A lot of work was completed by the programming team while using the Cowbot at Toro facilities in Bloomington, MN. Most of this work involved tuning the path planning and navigation software components to work better with the Cowbot dynamics. The programming team made one trip to the WCROC in Morris for a week of pasture/field testing during the last week of June. The programming team is also working on software that will allow the Cowbot to plan and execute a unique mowing path assuming the location of weeds in the pasture is known. This is different than the current plan which completely mows the selected test area. A weed to weed path has

the advantage of using much less energy when weeds are scattered throughout a pasture, but not densely enough to warrant mowing the entire area.

Activity 1 Status as of January 1, 2022:
The Cowbot software was modified to allow three different mowing patterns: back and forth on adjacent paths, back and forth skipping paths to reduce turning radius, and an inward spiral. All three were used in the final pasture test. For the final test, a 12 acre pasture was partitioned into 6 approximately 2 acre paddocks. The paddock size is a good approximation of how much area the cow herd at the WCROC would graze in a day or two. Three of the paddocks were mowed using a traditional tractor pulling a bat-wing style mower while the remaining three were mowed using the Cowbot with a different mowing pattern on each one. Mowing time, energy usage, and video were recorded for each run as well as a qualitative assessment of weed control effectiveness. In general, weed control effectiveness was best with the spiral pattern, worst with the skip path pattern, and was about equivalent to the tractor mowed paddocks using the adjacent path pattern. Recorded data on energy usage is still being analyzed and will be presented in the final report. The Cowbot took much longer to mow each paddock taking about 90 minutes per acre, but of course, there is no overtime pay for a robot!

The Cowbot performed reliably mowing its three assigned pastures over two days without any breakdowns or problems. All three mowing patterns were successfully followed and the Cowbot was able to navigate autonomously from the trailer to the starting point of each paddock and return to the trailer upon completion.

Final Update June 30, 2022
<u>The Cowbot Platform</u>
Cowbot is built on the Toro GroundsMaster 3280-D tractor platform which is available commercially and is powered by a 20 kW diesel engine. The platform has a long production history (first launched in 1973) with proven robustness and maneuvering capabilities. It makes for a good choice for the design of Cowbot as it provides sufficient power to operate the mowing implement needed to mow weeds in cow pastures. In line with the focus of the project to reduce carbon footprint in organic dairy production, Cowbot is designed to be powered on the farm using solar power. For this reason, the base platform was modified by replacing the diesel engine with a 100 V high-power 18kW liquid cooled Permanent Magnet AC (PMAC) electric motor powered by a 100V 28.8 kWH lithium battery pack. Cowbot is also equipped with a 6 kW level-2 onboard charger that allows the battery pack to be charged fully in about 6 hours using a level-2 charger. Cowbot is also fitted with the base platform's stock Roll Over Protection System (ROPS) and a canopy strengthened via the addition of front struts. The canopy is also used to provide mounting space for sensors and onboard computer on the Cowbot.

For autonomous control, two key subsystems of the base platform need automation - traction and steering. To achieve automated traction control we replace the manual-input (foot pedal with linkage) hydrostatic transmission control with an electronically-controlled hydrostatic transmission (e-Hydro). The traction subsystem receives speed commands from the traction pedal in manual mode and through navigation commands in autonomous mode. Steering on the Cowbot is controlled through a hydraulic cylinder equipped with a position sensor to provide steering feedback. An electronically-controlled solenoid valve is added to provide steer-by-wire functionality. In manual mode, the steering wheel pumps oil in and out of the cylinder, while in autonomous mode, the solenoid valve is used to pump the oil in and out of the steering cylinder. Autonomous steering commands (in degrees) are converted to a desired cylinder stroke length.

After replacing the stock deck mower with a more robust flail mower, Toro made mechanical modifications to the flail mower to increase its mowing height to better meet the needs of pasture management. The goal is to cut weeds soon after cows have grazed, but not to cut any more grass than needed. Other modifications were aimed at improving the stiffness of computer and sensor mounting methods. These modifications were because of the excessively rough terrain in WCROC cow pastures due primarily to gopher mounds. Pasture testing revealed the need for additional Cowbot improvements to be addressed by Toro including guards for sensors and oil filters that mount under the mower, larger caster wheels and mounts at the front of the flail mower, and new tires with better traction.

Autonomous Operation

Cowbot can operate in both manual and autonomous modes. In the manual mode, it is controlled by the traction pedal and steering wheel. In the autonomous mode, it receives steering and traction commands from the onboard computer. For safety considerations, Cowbot's autonomous mode is designed to be initiated by a human operator. Cowbot has four operating states/modes: Manual, Arm, Ready and Auto.

When autonomous operation is desired, the operator sets the Cowbot to Arm mode by pressing the arm button on the console. In Arm mode, the electronic steering system is activated, Cowbot states are recorded, the three onboard (wired) E-stops and the wireless E-Stop need to be enabled (to make sure the machine can be stopped any time for safety). Once the Cowbot is ready, the operator initiates the transition to Ready state by pressing the Arm button again. Ready state is solely a transition state and means the Cowbot is ready to operate autonomously. Cowbot will stay idle in this state waiting for the onboard computer to send a command for Auto mode which happens automatically after a 5 second delay if all systems are working properly.

Cowbot uses a GPS-based point to point inertial navigation system and is equipped with two GPS receiver units to provide high accuracy location and heading estimates. It is also equipped with front facing cameras and a lidar sensor to help with weed and obstacle identification, but research in this area was limited. The sensors connect to an onboard laptop computer that runs navigation software developed by University of Minnesota researchers. The Navigation software sends driving commands to the Cowbot's electrical subsystem including desired speed, desired steering angle, desired motor idle speed and operation commands including on/off and lift/lower for the flail mower. The interface between the laptop and Cowbot allows full operational and navigational control while relying on the Cowbot's electrical subsystem for the low level control of its components.

Safety Systems

Cowbot is designed to autonomously operate large weeding implements in challenging terrain on cow pastures making safety of operation a primary concern. A variety of operational safety systems have been implemented in the design.

- Operational Procedure: Unlike many existing agricultural robotic platforms, Cowbot qualifies as heavy machinery due to its size and power. Additionally, the intended operational environment in dairy farms is shared with livestock and human workers. In the current stage of development and agricultural autonomy, we think it is essential for a human operator to be aware that a large autonomous robot is operating on the pasture. To enforce this, we require that an operator initiates Cowbot's transition to Autonomous operating mode. As detailed above, the operator must go through a multi-step state transition process to enable Autonomous mode on the Cowbot.
- Bump Sensors: Cowbot is surrounded with force- activated bump sensors on all sides. In the event that the Cowbot runs into an obstacle, the bump sensor will activate and signal the motor controller to stop the motor. This will cause all hydraulics to deactivate and completely stop the machine.
- Flail Guard: A flail guard is deployed in the front of the mower by making a curtain of heavy chains that obstruct any objects thrown to the front by the spinning blades.
- Flashing Lights: When operating in Autonomous mode, a bright flashing beacon light mounted on top of the Cowbot turns on to attract attention and give a clear warning sign to anyone nearby.
- Wired E-Stop Switches: There are three wired one- press E-Stop switches on the Cowbot mounted in the front, back and on the operator console on the right side of the Cowbot. To initiate Auto mode, all E-stops must be active. In the event of unintended operation, an emergency stop can be initiated by pressing and engaging any of the three E-stop switches. On pressing an E-stop switch, Cowbot will be powered off and the motor will stop operating to completely disable its operations. Each of the E-stop switches must be disengaged to power on the Cowbot again.
- Wireless E-Stop Switch: A one-press wireless E-Stop switch is also provided with the Cowbot to allow an operator to stop it remotely when in Autonomous mode. It communicates with the Cowbot on the 2.4 Ghz band. The Cowbot will transition to autonomous mode only if the wireless E-Stop is turned on and remote connection is established. When the wireless E-Stop switch is engaged, Cowbot's controller will turn off the motor and exit Autonomous mode. This implementation is intended to ensure that the Cowbot can be safely and reliably disengaged when needed. In the case that the wireless E-Stop goes out of range of the Cowbot when it is operating in Autonomous mode, Cowbot will failsafe - the controller will turn off the motor and exit Autonomous mode. The wireless E-Stop must be disengaged before the Cowbot can be powered on again.
- Failsafe to manual: Any input on the traction pedal or steering wheel triggers failsafe behavior and transitions the Cowbot state to Manual. The Cowbot seat is also connected to a switch and an operator can be in or out of the seat, but a change of state in the seat switch while in Auto mode transitions the Cowbot state to Manual.

<u>Software</u>

Two software modules were developed by University of Minnesota researchers to accomplish autonomous mowing in pastures. One module is a path planner and the other is for navigation. Cowbot operation starts by setting up a GPS base station near the pasture and manually driving around the perimeter of the desired area to be mowed stopping at each corner to enter the GPS coordinates. The path planning module calculates an optimized mowing path to cover the pasture accounting for space needed for any turns. Three different path planners were developed to compare different mowing patterns; namely: adjacent path, skip path, and spiral. The adjacent path planner has the Cowbot mowing straight paths parallel to the longest side of the pasture and turning around at the end to mow the next pass overlapping the first pass. The tight nature of adjacent passes requires the Cowbot to make a light bulb shaped turn at the end of each row. The planner accounts for this turning space so the Cowbot never goes outside the boundary of the selected mowing area. The skip path planner operates in a similar manner to the adjacent paths planner but allows the Cowbot to accommodate its turning radius by skipping passes. This results in less space needed for turning around because the Cowbot is not making exaggerated light bulb turns, but also results in more mowing of already mowed paths in the turning space as the Cowbot returns to mow the skipped paths. The spiral planner has the Cowbot mowing around the perimeter of the pasture making roughly ninety degree turns at each corner in ever decreasing spirals until the end when it must make a larger turn to mow the last few passes.

The adjacent path and spiral planners are similar to how a human operator would typically mow a lawn or pasture. The skip path planner was an attempt to use the precise navigation afforded by the GPS base station and the geometry of Cowbot to create a possibly optimized mowing pattern that would be impractical for a human operator.

Testing

Many test runs were conducted at the Toro facility in Bloomington, MN, with University computer science researchers to test and tune the software modules. Several field tests each year were also conducted at the WCROC to collect data while mowing on pastures. Data from these tests were indispensable to the development of the final version of the Cowbot which combined a robust mechanical system with robust software.

For the final test, a 12-acre pasture was partitioned into six paddocks each between 1.5 and 1.9 acres in size. This paddock size is a good approximation of how much area the cow herd at the WCROC would graze in a day or two.

On October 7th and 8th, 2021, paddocks 1, 3, and 6 were mowed using the Cowbot autonomous pasture mowing robot using 3 different mowing patterns. Paddock 1 was mowed using adjacent east/west paths with “light bulb” turns at each end. Paddock 3 was mowed using east/west paths, but skipping some paths to allow more direct turns at each end, continuing until all paths were mowed. Paddock 6 was mowed using a spiral pattern.

The Cowbot performed reliably mowing its three assigned pastures over two days without any breakdowns or problems. All three mowing patterns were successfully followed and the Cowbot was able to navigate autonomously from the trailer to the starting point of each paddock and return to the trailer upon completion.

Paddocks 2, 4, and 5 were mowed using a bat wing rotary mower pulled by a tractor and powered by the tractor’s Power Take-Off (PTO). A spiral mowing pattern was used until enough room was mowed to allow the tractor to turn around at row ends. Then adjacent east/west paths were used to finish the area.

Mowing time, energy usage, and video were recorded for each run as well as a qualitative assessment of weed control effectiveness. A weed count was not done prior to mowing, but all pastures appeared to have similarly large amounts of weeds. Results are shown in the following table.

Paddock	1^C	2^T	3^C	4^T	5^T	6^C
Area (ac)	1.8	1.9	1.7	1.9	1.5	1.1
Time to Mow (min)	142	30.2	134	30.7	24.5	94
Energy (kWh)	15.6	53.9	17.0	54.8	43.7	10.1
Weeds Remaining	18	15	41	14	12	5

^C Mowed by Cowbot

^T Mowed by Tractor

Cowbot energy consumption averaged 9.3 kWh/acre compared to 28.8 kWh/acre for the diesel powered tractor. The Cowbot used significantly less energy to mow than our fossil fueled tractor, but also took significantly longer cover the same area averaging about 81 minutes per acre compared to just over 16 minutes per acre for the tractor. However, time to mow is not a real concern for autonomous mowers.

ACTIVITY 2:

Description: Design, Develop, and Field Test a Portable Solar-Powered Charging Station

The team will design, assemble, and test a portable, solar-powered charging station that can be trailered to the field location and allow proof-of-concept for robots to re-charge.

Beginning in July 2018, a solar-powered charging station will be designed by renewable energy scientists at the WCROC in Morris, MN. The charging station will include a cargo trailer, a 1 to 4 kW solar array that can be mounted to the trailer and easily disassembled / folded in for transport, a battery storage pack, and balance-of-plant components to allow for effective and efficient charging of the robotic mower in the field. The cargo trailer will also be sized to allow for transport of the mower to the pasture and outreach events.

Following completion of the charging station design, components will be purchased and assembled at the WCROC. Researchers at the WCROC will use an existing cargo trailer and battery bank. A solar PV system and balance-of-plant components will be purchased. The systems will be fastened into the trailer and an electrician will install the wiring for the solar PV system, battery bank, and charging station. The portable charging station will be inspected and commissioned prior to operation. Initial testing will measure power generation, battery storage capacity, discharge and recharge times, and field setup and charging time.

When field testing begins with the robotic mower in spring of 2020, the cargo trailer will be used to transport the mower to the pasture. The portable charging station will be placed in or near the pasture to allow efficient recharging of the robotic mower. As the mower's power is diminishing, a signal will be sent to the autonomous control to return to the charging station. When the mower returns, the charging system will be manually connected and the robotic mower's batteries will be re-charged. A future goal (not a deliverable of this project) is to enable autonomous connection of the robot with the charging station. Throughout the grazing season, the portable charging station will be tested and variables recorded include energy production, effective energy stored, efficiency, number of charges and discharges, time required for charging, and labor required. The mower will be recharged at the farm site using on-site renewable energy generation when not in use mowing pastures. The data will be analyzed and included in the final report.

The portable charging station will be demonstrated to farmers and land managers through tours, workshops, and events such as Farmfest.

Summary Budget Information for Activity 2:	**ENRTF Budget:**	**$ 82,224**
	Amount Spent:	**$ 77,415**
	Balance:	**$ 4,809**

Outcome	**Completion Date**
1. Design a portable hybrid solar PV and electric storage system for charging	*2/1/2019*
2. Integrate solar PV, electric storage, and a charging station on a trailer	*6/1/2019*
3. Field test the portable solar PV charging station and on-board solar at the WCROC	*6/1/2021*
4. Demonstrate the portable solar PV charging station at state-wide events	*6/30/2021*

Activity 2 Status as of January 1, 2019:
The mower onboard battery charger will interface with a standard level 2 electric car charger. A trailer mounted solar PV array will be designed with a battery bank to produce the 240 VAC power needed by the car charger. Once the mower's charging specifications and energy usage are finalized, the solar array and battery bank can be sized and purchased.

Activity 2 Status as of July 1, 2019:
A 3 kW solar PV array along with eight 375 AH batteries and the necessary electronic equipment (charger controller and inverter) have been purchased from a Minnesota distributor (Northwest Renewable Energy LLC). Work is underway to design a system to mount the solar panels on a cargo trailer. A level 2 car charger has also been purchased to provide the charging interface with the mower's battery.

Activity 2 Status as of January 1, 2020:
An electrician has been contracted to wire the solar panel/battery system in a WCROC cargo trailer. Ten 330 Watt solar panels have been procured for the charging station. Each panel measures about 40" by 80" meaning that only four panels can fit on the roof of the cargo trailer. A drawer-like arrangement has been designed to allow ten panels to fit on the trailer roof. Two sets of three panels each will be mounted with drawer slides under a fixed layer of four panels. The two slide mounted panel sets will slide out in opposite directions when the charging station is deployed and slide back under the fixed panels for transport. Trailer modifications will be completed this winter and commissioned next spring.

Activity 2 Status as of July 1, 2020:
Solar panels have been mounted to the roof of a WCROC cargo trailer as planned and a box containing eight 6 volt batteries was secured inside the trailer by WCROC employees. A local electrician completed wiring the cargo trailer as a solar charging station. This included installing a charge controller for battery charging, an inverter to convert battery DC current to AC, and a level 2 car charger which will interface

with the cowbot. During commissioning the trailer it was discovered a few of the solar panels were wired backwards and a couple of the wires from the panels were too short to allow full extension of the solar panel “shelves”. A few specialty tools and supplies were procured and WCROC employees resolved these issues. An electric vehicle (Chevy Bolt) was connected to the trailer charger and charged until the battery bank state of charged reached its lower limit automatically shutting down the inverter. The batteries came to full charge after a day of charging as expected. The trailer is commissioned and operationally ready for pasture testing with the cowbot.

Activity 2 Status as of January 1, 2021:
The solar charging trailer was deployed in the pasture and was able to charge the Cowbot on site. The charging trailer worked as expected and is fully operational.

Special loading ramps were made to support the Cowbot weight with minimal deflection and provide enough length to prevent the flail mower from contacting the ramp while loading. Toro made modifications to the cowbot canopy so it could be folded allowing the cowbot to fit into the charging trailer. The cowbot was loaded into the trailer confirming the modifications worked.

Activity 2 Status as of June 30, 2021:
The charging trailer was used to move the Cowbot from Toro facilities to Morris and charge the mower. The charging trailer is working as designed and no further modifications are planned.

Activity 2 Status as of January 1, 2022:
The charging trailer worked well delivering the Cowbot to the pasture for the final mowing test. It was set up at the entrance to the pasture with both rows of movable solar panels extended and pinned in place. The Cowbot returned to the trailer after mowing each paddock and was then connected for recharging. The trailer can recharge the Cowbot in about the same amount of time that it takes to mow. In other words the charging rate is similar to the discharge rate while mowing. The energy required to mow the paddock size used for the final mowing test was about the limit of what could be stored in the charging trailer’s battery pack. Moreover, the battery pack is very heavy (~900 lbs.) and had to be placed at the very front of the trailer to allow room for the Cowbot. The trailer, consequently, is very heavy on the tongue which makes it more difficult to tow. If project funding allows, a lithium ion battery pack will be purchased to increase the trailer energy storage capacity and improve towing characteristics.

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An autonomous, electric powered, pasture mower needs two external things to successfully operate in a remote pasture: a means of transport to the pasture and a means of recharging its batteries at the pasture. Both needs were satisfied by adding solar panels and a battery storage system to an enclosed cargo trailer. The trailer is a tandem axle, V-nose model 14 feet long by 7 feet wide.

Several factors must be considered when designing an off-grid solar/battery system. Chief among these are the power and energy requirements of the electrical load and how long the storage system must supply that load without sunlight. In this case, the load is the Cowbot’s battery pack which contains 29 kWh of energy when fully charged. For perspective, that is about half the battery size of the all-electric Chevy Bolt. Ideally, the trailer and Cowbot batteries would be recharged daily since the Cowbot can operate about 3 or 4 hours before recharging.

The next decision is to determine the degree of discharge (DoD) that will be allowed on both battery packs (Cowbot and trailer). There is an inverse relationship between DoD and battery life meaning that allowing batteries to discharge more will reduce the number of charge/discharge cycles the battery can provide. Moreover, allowing the mower battery to discharge too much could lead to the mower being stranded in a pasture if it finishes mowing far from the charging trailer. A DoD of 35% was selected for the Cowbot as a reasonable compromise between mowing capacity, battery life, and reserve capacity leading to a daily recharging load for the trailer battery pack of 18.9 kWh.

The average solar insolation in central Minnesota during the summer months means a solar array of about 3.1 kW is required to meet the daily load. Ten panels will provide a 3.25 kW array satisfying the load requirement, but only four solar panels can fit on the roof of the trailer without extending over the sides. Brackets were designed and attached to the trailer roof to hold four fixed panels high enough above the roof to accommodate two rows of three panels each underneath the fixed panels. The lower two rows of panels are mounted to fully extending, heavy-duty, drawer slides allowing each row to slide out – one to the left side of the trailer and one to the right side – for access to sunlight. Two pins retain each moveable panel row in the retracted position for travel or in the extended position for battery charging.

Degree of Discharge is also an important factor in designing the trailer battery system in addition to battery type, voltage, and discharge rate. When this system was designed lithium ion batteries were relatively expensive so deep-cycle lead acid batteries were selected. Eight 6 volt batteries are connected in series to provide a 48 volt battery pack with a combined 18 kWh of storage capacity. Reserve capacity and battery life are of lesser concern for the trailer batteries than for the Cowbot battery, but even with a DoD of 0%, the battery pack will be a little short of the desired capacity. When designing a stationary battery system good practice is to round up all load estimates and battery quantity calculations to err on the safe side, but with a mobile battery system there are other considerations. Namely, each battery weighs 115 lbs resulting in a total battery pack weight of 920 lbs and the pack must be placed in the front of the trailer to allow room for the mower. This means the battery pack weight is mostly added to the tongue weight of the trailer. While a larger battery pack would better meet the load requirements, trailer towing considerations led to the slightly undersized battery pack.

Balance of system components include a PV combiner panel, charge controller, power inverter, and AC load center. Solar panel output wires are combined and fused in a PV combiner box which then feeds directly into a charge controller. The charge controller manages the battery charging process. The DC output from the battery pack is wired to a power inverter where electricity is inverted into AC current and fed to the load center to be distributed to any AC loads. In this case the AC loads are standard 120V outlets and a 240V, Level 2 electric vehicle charger made by Clipper Creek.

Having almost a thousand pounds of batteries in the nose of the trailer made trailer hook-ups very difficult and created tongue weight issues for standard trucks. These issues were resolved with an electric trailer jack and replacing the lead-acid batteries with wall-mounted lithium iron phosphate batteries. This reduced the battery weight about in half and allowed the batteries to be mounted on the trailer walls closer to the axles greatly reducing tongue weight. Lithium based batteries can be discharged to a greater degree and will last for more charging cycles than their lead-acid counterparts.

The solar charging trailer worked very well for providing power for the Cowbot at remote pasture sites and could also be used as a portable power station for other purposes such as emergency power during utility power outages. Mounting solar panels to the roof of the trailer caused no issues with over the road travel, but water leaking through one of roof penetrations created to attach the panels did lead to an inverter malfunction and repair.

ACTIVITY 3:
Description: Develop and Field Test Autonomous Vehicle(s) Capable of Early Weed Control in Row Crops

The team will design, assemble, and field test at least one and up to two autonomous vehicles capable of weed control in row crops approximately 12 inches and less in height.

Beginning in July 2018, the project team will source UTV and similar platform vehicles that can be powered by renewably produced energy. The vehicles will most likely be four wheel drive, convertible to autonomous operation, and capable of incorporating tracks. Up to two types of platforms may be tested.

Beginning in November 2018, up to four different types of weeding implements will be designed, fabricated, installed, and tested at the WCROC. Initial concepts are the single and-/-or combined use of a rotary hoe, spring tooth harrow, rotary harrow, and scrapper blades. The effectiveness of the implements will initially be tested with a non-autonomous vehicle platform on row crops at the WCROC during the spring and summer of 2019.

Beginning in July 2019, autonomous controls will be designed, installed, and tested on the vehicles. The navigation and awareness sensors, hardware, and software within the mower project will be adapted for these vehicles. GPS-based navigation will be complemented with a vision-based system to meet the higher navigation needs for weeding in row crops.

The row crop vehicles will be converted to an autonomous ready state with anticipated control enabled to start, shutoff, steer, change of operating speed, implement lift, and change of direction (FWD/REV). We anticipate control parameters that will prevent the vehicle to be operated outside of normal /safe operating parameters. These control parameters will include operating speed, cornering speed, engagement of implements, and motor RPMs.

Researchers in the U of MN Department of Computer Science and Engineering will again further develop a GPSbased system developed in Activity 1 to allow the vehicle to navigate through the row crops using predetermined GPS points. If GPS accuracy is not sufficient, a vision and LiDAR based system for following rows and turning will be developed. A LiDAR system will be utilized for hazard detection and avoidance and to signal when necessary to lift the implement over obstructions or end rows or shut down the vehicle. Simultaneously, researchers in the U of MN Department of Bioproducts and Biosystems Engineering will consult Computer Science researchers in the overall development of the autonomous vehicles. The project team will review the design and integration of the integrated vehicles and implements identifying potential hazards (including but not limited to mechanical failure, obstacles, and wildlife and/or human interactions), designing control systems to mitigate hazards, and incorporate redundant controls in case one or more systems fail. The system will be designed and constructed to "fail safe".

Commissioning will include a series of operational tests for basic operation as well as HazOp / fail safe verification. Once the autonomous vehicle(s) have been commissioned and certified operational by the research team, the row crop weeding autonomous vehicles will be field tested within organic certified corn and soybean fields at the U of MN West Central Research and Outreach Center (WCROC) near Morris, MN.

Beginning in the spring of 2020, the autonomous row crop weeding vehicle(s) will be put through a series of initial operational tests and then will move into field tests. Initial testing will include line following, row and obstacle detection, and the coverage with integrated obstacle avoidance. For the field tests, approximately 10 acre row crop plots of corn and soybeans will be utilized. The row crops will be divided into 3 replications each consisting of at least three treatments- Non-Autonomous Implement, Autonomous Implement #1, Autonomous Implement #2, ETC. The first treatment will be a control utilizing a tractor and implement driven by a WCROC employee. The second treatment is anticipated to be the autonomous vehicle and rotary hoe. The third and subsequent treatments will include the autonomous vehicles and different implements. Variables will be measured such as time required to complete row crop weeding (acres per hour), energy consumed (kWh or fuel / acre) , effectiveness of weed control (weed counts / acre extrapolated from smaller sample size), row crop plants per acre (extrapolated from smaller sample size) hours of labor required, maintenance / repairs required,
and navigation / hazardous issues encountered. Refinements will be made to the autonomous vehicles and implements throughout the test period including the possibility of multiple passes or combinations of implements. Testing will continue throughout the early growing season (generally May through early June).

The autonomous vehicle capable of early weed control in row crops will be demonstrated to farmers and land managers through tours, workshops, and events such as Farmfest.

Summary Budget Information for Activity 3: **ENRTF Budget: $ 310,716**
Amount Spent: $ 265,318
Balance: $ 45,398

Outcome	**Completion Date**
1. Design, develop, and test a UTV or comparable platform to weed in row crops	*7/1/2019*
2. Design, develop, and test row crop weed implements on a UTV or comparable platform	*7/1/2019*
3. Develop navigation / logic systems to allow for autonomous operation	*1/1/2020*
4. Develop and test safety and fail-safe logic and protocols	*4/1/2020*
5. Integrate and commission UTV or comparable platform with navigation systems	*4/1/2020*
6. Field test autonomous weeding vehicle within row crops at the WCROC	*6/20/2022*
7. Display / demonstrate the autonomous vehicle at state-wide events	*6/30/2022*

Activity 3 Status as of January 1, 2019:

Initial meetings with crop specialists have been held to select the type of weeding implement that is likely to perform well behind a smaller electric vehicle. Prototypes will be constructed this winter for spring testing and refinement.

Activity 3 Status as of July 1, 2019:
A prototype weeding implement that can work as a harrow or disc weeder has been built to mate with an electric Polaris Ranger vehicle. The weeding implement will be tested and refined as needed in the coming months. It will also be adapted to work with the selected field vehicle, be it the Ranger or a new TORO vehicle.

Activity 3 Status as of January 1, 2020:
The project team realized that procuring a new vehicle for pulling row crop weeding implements was going to duplicate a lot of work in making the new vehicle drive by wire and establishing protocols for the navigation software to communicate with the vehicle control system. Drive by wire means that all essential vehicle functions like steering and throttle control need to be electronic not mechanical. All of this work has already been done on the Cowbot so it was suggested to use the Cowbot to pull the weeding implements. Because the Cowbot uses rear wheel steering, the best pulling arrangement for it would be to remove the flail mower from the front and attach the weeding implement there. This requires driving the Cowbot in reverse to simulate a typical tractor/implement arrangement. Since the Cowbot will be autonomous, driving in reverse is not seen as an issue.

This idea was tested on a field at the WCROC in early November. Both a harrow and rotary hoe attachment were demonstrated with the Cowbot. Of primary concern was whether the Cowbot would have sufficient towing capacity. Both implements were pulled without apparent problems. Vehicle handling and mechanical connection logistics were also deemed to be nonissues.

Activity 3 Status as of July 1, 2020:
Cowbot programming changes have been made to allow the mower to go faster in reverse. Reverse speed is normally restricted for driver safety reasons, but the restricted speed is a bit too slow for pulling weeding implements. The normal speed restriction will not be necessary while the mower is operating autonomously. Delays in testing this spring caused by COVID-19 resulted in missing the early term crop phase being targeted for weeding in this activity. When Cowbot testing resumes this summer autonomous testing with the prototype weeding implements will be conducted in preparation for in-field testing next spring.

Activity 3 Status as of January 1, 2021:
Delays to the start of pasture testing resulted from a University shutdown due to the COVID pandemic. Moreover, new approval procedures were developed at the University and Toro to allow work to continue on site and to allow off-site personnel access. These delays shortened the test season this summer and did not allow enough time for testing with towed weeding implements to progress. Work will be done this winter on the path planning code to get it ready for testing next spring.

Activity 3 Status as of June 30, 2021:
Much of the off-season work this winter was devoted to developing code to allow the Cowbot to pull a weeding implement while driving in reverse. This is difficult for a human driver because the seat cannot be reversed but is not a problem for an autonomous vehicle. Much tuning of the path planning and navigation code was needed because the weeding implement makes the overall combined vehicle length much longer. Moreover, the vehicle location that needs to be controlled is the center of the weed implement which is much further from the vehicle center than the flail mower (the flail is removed prior to attaching an implement). While the mower is driving in reverse it becomes a front wheel steered vehicle which also required some additional tuning. Testing of a rotary hoe implement was done in Morris during the last week of June in a freshly cut oat field. The Cowbot was able to cover a field section pulling the hoe in reverse at a higher speed which is desirable for hoeing. However, because the implement attaches to the Cowbot body and not the chassis, unexpected stresses were induced into the brackets that attach the body to the chassis. A couple welded support plates were broken while testing. This is not a catastrophic failure but will need to be addressed by Toro when the vehicle is returned. A weeding implement will not be pulled again until the situation has been remedied.

Activity 3 Status as of January 1, 2022:
The broken chassis brackets from the previous test were repaired and reinforced by Toro. While the Cowbot is, therefore, theoretically able to pull an implement in reverse, this configuration will not be tried again. The previous testing of this configuration was sufficient to demonstrate the concept, but further testing without a redesign of the implement/Cowbot connection method could jeopardize continued testing in the primary pasture mowing configuration. Redesigning the connection method is outside the scope of the contract with Toro.

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A universal frame was designed and built at the WCROC to attach to the front deck of the Cowbot with the flail mower removed. The frame could accept a modified rotary hoe or spring harrow weeding implement. Software modifications were made to allow the Cowbot to drive in reverse pulling the weeding implement through a field with early-stage row crops. The decision to drive in reverse for this configuration was made because the base mower is a rear steering model so attaching the weeding implement to the back of the Cowbot would put the steerable wheels in between the Cowbot's non-steerable front wheels and the implement frame's caster wheels making control difficult and unpredictable. Toro made modifications to the mower's low level control system to allow a faster speed in reverse than would be available on a stock mower. These types of weeding implements are typically driven at 7 to 9 mph which would be considered an unsafe speed for a human driver driving in reverse.

The weed implement/Cowbot configuration was tested several times at the WCROC but was abandoned after some structural damage incurred to the Cowbot chassis due to the unusual loading condition created by the implement frame. Moreover, the combined Cowbot/implement frame proved to be too long for stable driving at the desired speeds making turns problematic. Field testing did show the weeding implements operated in a similar manner to their conventional counterparts producing similar results. The path planning and navigation software developed and proven in pasture mowing was also successful in this environment demonstrating that weeding implements could be pulled by an autonomous vehicle in early-stage row crops.

V. DISSEMINATION:

Description:

Several different mechanisms will be utilized to disseminate the information. First, the mowing robot will be demonstrated to farmers and land managers at workshops, field days, and a large event such as Farmfest. Information learned in the project will be posted on-line at the University of Minnesota West Central Research and Outreach Center site. As the project achieves milestones, news briefs will be sent to local and regional news outlets as well as agricultural trade magazines such as The Farmer and The Land to report progress.

Status as of January 1, 2019:

No work has been completed yet on project dissemination.

Status as of July 1, 2019:

The prototype pasture mower, solar charging equipment, and the prototype row crop weeding implement were all displayed at the Midwest Farm Energy conference held at the WCROC on July 10th.

Status as of January 1, 2020:

The Star Tribune featured the Cowbot on the front page of their September 7th, 2019, Sunday edition.

Status as of July 1, 2020:

The cowbot will be featured in the Legacy magazine produced by the University of Minnesota Foundation later this summer. Pioneer PBS is planning to feature the cowbot in an upcoming episode of the "Prairie Sportsman". They are planning to film here during testing in July. The planned demonstration of the cowbot at FarmFest will not occur this August because FarmFest has been cancelled due to COVID-19.

Status as of January 1, 2021:

An LCCMR funded local PBS television show, "The Prairie Sportsman", interviewed the project team and filmed the Cowbot in action on September 21, 2020. A segment is expected to run on the show in May 2021.

Status as of June 30, 2021:

The story produced by the Prairie Sportsman show aired in March and can be viewed here: https://video.pioneer.org/video/autonomous-mower-2ceqti/

The Cowbot will be demonstrated at Farm Fest this year from August 3rd through the 5th. There will be two mowing demos each day at 10 am and 1 pm. The Cowbot and charging trailer will be displayed in a booth the rest of the time. Farm Fest organizers are using the cowbot demos as part of their marketing campaign for the entire show.

Status as of January 1, 2022:

Farm Fest organizers provided an extra-large booth area (100' x 300') of unmown alfalfa at a discounted rate to provide space for live demonstrations of the Cowbot. They also used these demonstrations as one of the handful of events listed in their primary marketing materials for the event. A tent was set up with photos and information about the Cowbot. Cowbot demonstrations were conducted twice on each of the three days of the event. These demonstrations attracted crowds and elicited lots of questions.

The project team was interviewed by a couple farm publications and was mentioned on MPR by a reporter who attended the event.

Final Update June 30, 2022
Several academic papers were published relating to technology used to design mowing paths and control the Cowbot:

1. Maini, Parikshit, Burak M. Gonultas, and Volkan Isler. "Online coverage planning for an autonomous weed mowing robot with curvature constraints." *IEEE Robotics and Automation Letters* 7, no. 2 (2022): 5445-5452.
2. Wei, Minghan, and Volkan Isler. "Predicting energy consumption of ground robots on uneven terrains." *IEEE Robotics and Automation Letters* 7, no. 1 (2021): 594-601.
3. Wei, Minghan, and Volkan Isler. "Building energy-cost maps from aerial images and ground robot measurements with semi-supervised deep learning." *IEEE Robotics and Automation Letters* 5, no. 4 (2020): 5136-5142.
4. Maini, Parikshit, and Volkan Isler. "Choosing Classification Thresholds for Mobile Robot Coverage." In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 2630-2635. IEEE, 2020.
5. Wei, Minghan, and Volkan Isler. "Energy-efficient path planning for ground robots by combining air and ground measurements." In *Conference on Robot Learning*, pp. 766-775. PMLR, 2020.
6. Wei, Minghan, and Volkan Isler. "Air to ground collaboration for energy-efficient path planning for ground robots." In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1949-1954. IEEE, 2019.

The Cowbot was demonstrated to farmers and land managers at several events like the Midwest Farm Energy Conference at the WCROC in 2019 and 2022. It was also featured in an episode of the PBS television show "The Prairie Sportsman" along with interviews with several project team members airing in March 2021. The Cowbot was a featured live demonstration at a state-wide expo in August 2021 called Farmfest. Finally, the Cowbot appeared in several print media articles including the Star Tribune and AgWeek.

VI. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview:
See attached budget spreadsheet

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: One solar PV system will be purchased for not more than $13,600. The solar system will include solar panels, bracketing, inverter, battery pack, balance-of-plant, and a charging station. One or more of these components may need to be purchased separately. One Velodyne E-Puck LiDAR and related components will be purchased for a price not to exceed $10,000. The LiDAR will be used to make the mowing robot aware of potential hazards in the general area and then a signal will be sent for the system to shut down or to avoid the hazard.

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 4.0 FTE

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: ~0.33 FTE

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
The Toro Company	$ 124,000	$ 300,000	In-kind contribution of equipment and labor
State			
	$	$	
TOTAL OTHER FUNDS:	**$ 124,000**	**$** 300,000	

VII. PROJECT
STRATEGY: A.
Project Partners:
Partners receiving ENRTF funding
Edric Funk, Director of Toro Center for Advanced Turf Technology, and Jack Gust, Research and Development
Chief Engineer, The Toro Company, $99,000 ($37,000 labor and $62,000 components and supplies) , Convert a Toro diesel mower to electric power including adding an electric motor and battery storage. Acquire and integrate a flail mower. Assist in integrating controls for autonomous operation and in commissioning and testing of the mower system. The Toro Company will provide an in-kind match of $124,000 in equipment and labor.

B. Project Impact and Long-term Strategy:
Successful development of economic solar-powered robotic systems for weed control in pastures and fields will have significant positive impacts to Minnesota's air, land, water, and wildlife resources. The long term strategy is to develop marketable robotic weed control systems that can be manufactured by Minnesota companies and utilized by Minnesota farmers and land managers; and expand the utilization of solar PV within the State. A Minnesota original equipment manufacturer (OEM) is participating on the project team and will provide invaluable experience in developing products for the commercial market. The project team anticipates submitting a future funding request for a second phase of this project which will involve the use of robots to control weeds in row crops.

C. Funding History: This is a novel project. The Project Manager has received LCCMR funding in the past but for unrelated projects.

Funding Source and Use of Funds	Funding Timeframe	$ Amount

		$

VIII. REPORTING REQUIREMENTS:

- **The project is for 4 years, will begin on 07/01/2018, and end on 06/30/2022.**
- **Periodic project status update reports will be submitted January 15th and July 15th of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2022**.

IX. VISUAL COMPONENT or MAP(S):

Conventional weed control processes typically use large, diesel-powered sprayers and chemical herbicides are broadcast across crop fields and pastures. Control of weeds is very effective, however, there are unintended and potentially harmful consequences.

Our concept is to evaluate the control of weeds in pastures and row crops using robots powered by the sun. Our project team will utilize off-the-shelf as well as pre-commercial technologies which will be modified to operate autonomously in the mowing of pastures and weeding of fields.

Early Cowbot Field Test at the WCROC

Cowbot Final Mowing Test in Paddock 6

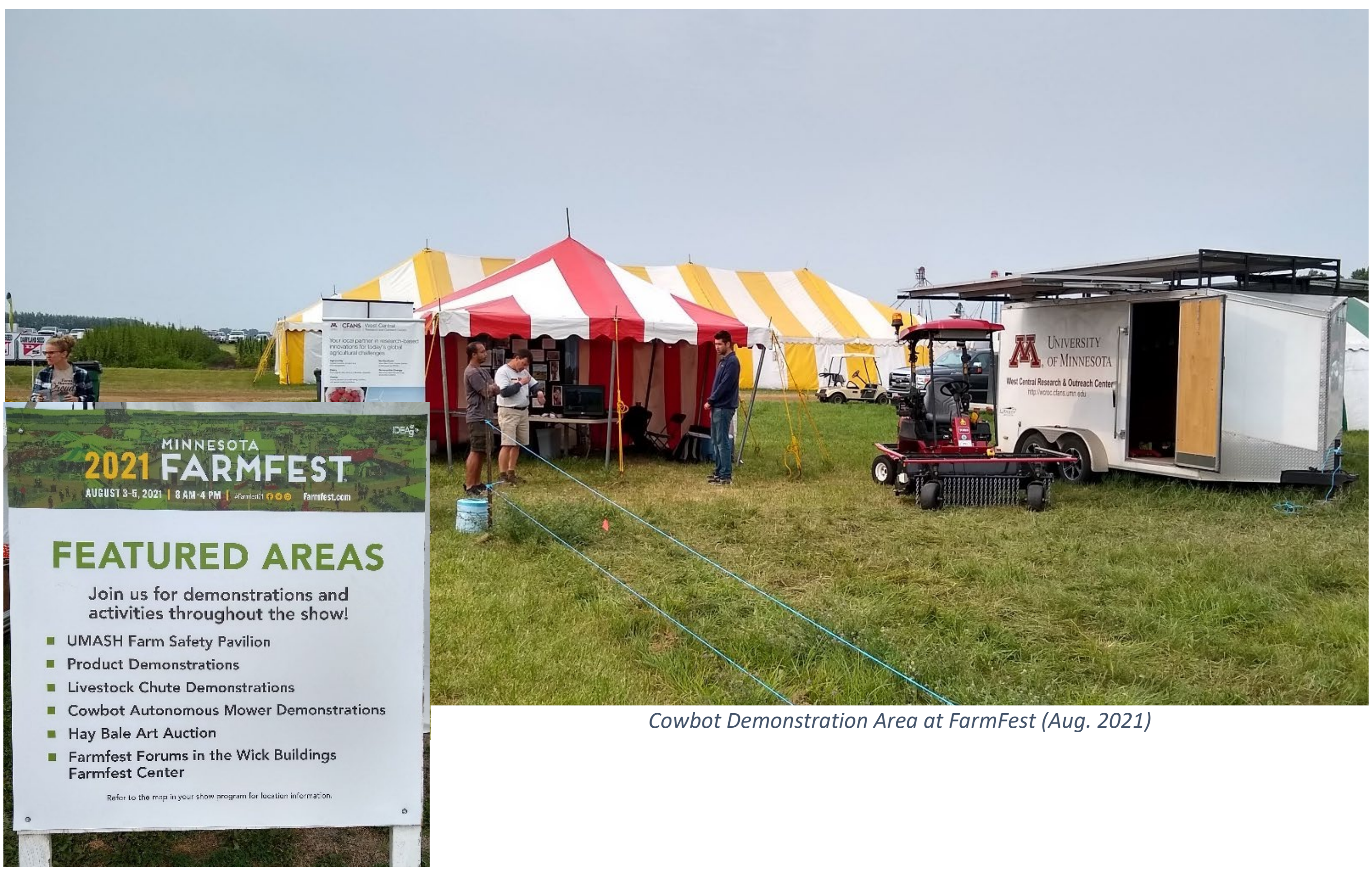
Cowbot Field Test with Rotary Hoe Weeding Implement Attached

Cowbot Final Mowing Test Paddocks

If successful, fossil-based diesel fuel and chemical herbicide use as well as harmful side-effects will be significantly reduced. Local production of clean energy will be increased. Farmers will have new timesaving tools for effective weed control and Minnesota companies will benefit by leading the manufacture of new solar-powered robotic technologies.

Cowbot Charging in Pasture with Solar Trailer

Solar Trailer Equipment with Original Lead-Acid Batteries



Cowbot Demonstration Area at FarmFest (Aug. 2021)

Environment and Natural Resources Trust Fund
M.L. 2018 Project Budget -Final

Project Title: Agricultural Weed Control Using Autonomous Mowers
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08d
Project Manager: Eric Buchanan
Organization: Regents of the University of Minnesota
M.L. 2018 ENRTF Appropriation: **$** *750,000*
Project Length and Completion Date: 4 *Years, June 30, 2022*
Date of Report: August 18, 2022

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	REVISED BUDGET 03/7/2022	TOTAL SPENT	TOTAL BALANCE
BUDGET ITEM			
Personnel (Wages and Benefits)	$ 537,699	$ 495,295	$ 42,404
Project Coordinator - Eric Buchanan, $88,934 (FTE Yr 1 at 10% and Yrs 2-3 at 50%) 33.5 % fringe rate, 2.25% COLA -U of MN WCROC			
Researcher, $75,440 (10 % FTE Yr 1, 50% Yr 2, 40% Yr 3) 33.5% Fringe Rate, 3% COLA - U of MN Bioproducts and Biosystems Engineering			
Farm Technician - Fabrication and testing of weeding implements, $11,898 (FTE Yr 1 - 25%) 27.2% Fringe Rate, U of MN WCROC			
Post Doctorate Research Associate, $81,830 (50 % FTE-Yrs 1-2) 23% Fringe Rate, 3% COLA - U of MN CS&E			
Graduate Student Research Assistant #1 to train under Dr. Volkan Isler with autonomous mower - CSE, $132,760 (Yrs 1-3, 9 months in final year, 50% FTE, hourly rate $24.92 plus tutition at $19.90 / AY hr, 17.7% fringe)			
Graduate Student Research Assistant #2 to train under Dr. Volkan Isler with autonomous row crop weeder - CSE, $132,760 (Yrs 1-3, 9 mo. in final year, 50% FTE, hourly rate $24.92 plus tutition at $19.90 / AY hr, 17.7% fringe)			
Professional/Technical/Service Contracts			
Subcontract with The Toro Company, Bloomington, MN for labor ($37,000), components, and supplies to convert a diesel powered mower to electric power and to assist and provide a location to integrate and commission the autonomous hardware and software being developed at the U of MN.	$ 99,000	$ 99,000	$ -
Contract with an electrician to complete wiring of the portable solar-powered charging station. University of Minnesota professional service policy will be followed in securing services of an electrician to perform this work.	$ 2,286	$ 2,286	$ -
Equipment/Tools/Supplies			
Lab supplies for Dr. Isler including a laptop computer with NVidia GPU, GPS systems, multiple cameras, component enclosures, and supplies for wiring, soldering, etc.	$ 9,599	$ 9,599	$ -
Materials to fabricate custom weeding implements (steel, part assemblies, wheels, paint, welding rods, etc.)	$ 2,628	$ 2,628	$ -
Equipment to upgrade and adapt Toro vehicle for pulling weed control implements and improve drive by wire capability.	$ 21,000	$ 20,444	$ 556
Supplies for Buchanan including energy meters / sensors, and supplies for wiring and securing systems on the portable charging station.	$ 1,526	$ 1,526	$ -
Capital Expenditures Over $5,000			
Solar PV system which will include solar panels, bracketing, inverter, battery pack controller, balance-of-plant and charging station	$ 28,972	$ 24,163	$ 4,809
Velodyne E-Puck LiDAR and components	$ 10,000	$ 9,900	$ 100
Travel expenses in Minnesota			
Total travel expenses in MN - combining individual travel budgets- Twelve trips by CSE and BBE Faculty from Saint Paul to Morris, MN (330 miles @ $.56 / mi) -Lodging and meals for CSE and BBE Faculty in Morris (3 people / 6 nights @ $80 / room and $40 ea for meals) -WCROC Staff travel from Morris to Twin Cities (330 miles and 4 trips @ .56, 2 nights @ $120 / room and $40 ea for meals) -Travel, lodging, and meals for one in-state outreach event FarmFest (4 people, 4 days /3 nights, 2 trips, 400 mi @$.56/mi, $120 / room, and $40 ea for meals)	$ 15,045	$ 15,045	$ -
Other			
Computer Services Fee - Standard fee charged by U of MN Department of Computer Science and Engineering for use of computers by staff for programming and analysis.	$ 18,081	$ 15,743	$ 2,338
Farmfest Exhibitor Fee, Tickets, Signage, and Display	$ 4,164	$ 4,164	$ -
COLUMN TOTAL	**$ 750,000**	**$ 699,793**	**$ 50,207**

Cowbot: System Design and Field Evaluation of an Autonomous Weed Mowing Robot for Cow Pastures

Parikshit Maini, Burak M Gonultas, Jim Gaebel, Eric Buchanan,
Minghan Wei, Jack Gust, Pete Kennedy, Pratik Mukherjee and Volkan Isler

I. System Design

In this section, we present Cowbot's system components and discuss the details of its design. We first introduce the base platform used for Cowbot in section I-A and discuss the modifications made to make it suitable for autonomous operations on the pasture. Next, we present operating modes and safety features of Cowbot. We then present the details of the solar-powered charging trailer that is used to charge the Cowbot on the pasture and allows it to be permanently stationed on the farm.

A. The Base Platform

Cowbot is built on the Toro GroundsMaster 3280-D tractor platform which is available commercially and is powered by a 20 kW diesel engine. The platform has a long production history (first launched in 1973) with proven robustness and maneuvering capabilities. It makes for a good choice for the design of Cowbot as it provides sufficient power to operate the mowing implement needed to mow weeds in cow pastures. In line with the focus of the project to reduce carbon footprint in organic dairy production, Cowbot is designed to be powered on the farm using solar power. For this reason, the base platform was modified by replacing the diesel engine with a 100 V high-power 18kW liquid cooled Permanent Magnet AC (PMAC) electric motor powered by a 100V 28.8 kWH lithium battery pack. Cowbot is also equipped with a 6 kW level-2 onboard charger that allows the battery pack to be charged fully in about 6 hours using a level-2 charger. Cowbot is also fitted with the base platform's stock Roll Over Protection System (ROPS) and a canopy strengthened via the addition of front struts. The canopy is also used to provide mounting space for sensors and onboard computer on the Cowbot.

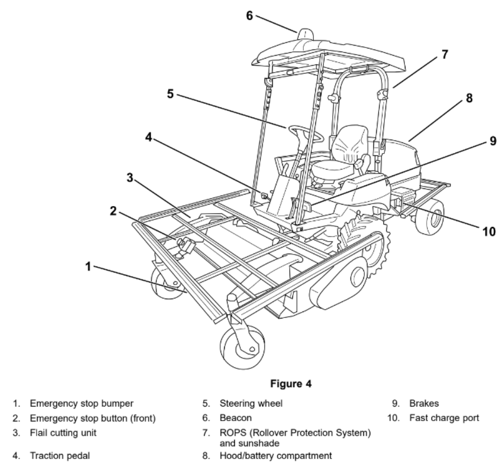


Fig. 1: Annotated image showing different parts of the Cowbot. source: Cowbot manual

For autonomous control, two key subsystems of the base platform need automation - traction and steering. To achieve automated traction control we replace the manual-input (foot pedal with linkage) hydrostatic transmission control with an electronically-controlled hydrostatic transmission (e-Hydro). The e-Hydro adjusts the transmission swash-plate through electronic control of a forward/reverse coil. The traction subsystem receives speed commands from the traction pedal in manual mode and through navigation commands in autonomous mode. A PID control algorithm that uses speed feedback is used to control the e-Hydro swash-plate to achieve the target speed. Steering on the Cowbot is controlled through a hydraulic cylinder equipped with a position sensor to provide steering feedback. An electronically-controlled solenoid valve is added to provide steer-by-wire functionality. In manual mode, the steering wheel pumps oil in and out of the cylinder, while in autonomous mode, the solenoid valve is used to pump the oil in and out of the steering cylinder. The cylinder's stroke length is mapped to centerline steering angle. Autonomous steering commands (in degrees) are converted to a desired cylinder stroke length (analog voltage) using a lookup table. The controller utilizes a proportional control loop to adjust the cylinder stroke to achieve the target steering angle.

When mowing cow pastures to remove weeds, it is desirable to not mow the grass very short to allow it to grow back quickly. Base on recommendations from dairy scientists, we determined a 20 cm height-of-cut (HOC) to be ideal for cow pastures. The common HOC for grass turfs is usually no more than 10 cm. As a result Cowbot's base platform equipped with a rotary cutting implement, was also designed to admit up to 10 cm ($\sim$ 4") HOC. During initial tests, rotary mowers were found unacceptable due to the inability to achieve the large HOC, high power consumption in pasture conditions and the risk of flying debris thrown at high speeds. For this reason, the Cowbot was equipped with a flail cutting implement with 60 inch ($\sim$ 152 cm) wide deck custom mounted to provide 20 cm HOC. Incorporating the flail is a challenging task, because the added vertical translation of this taller, close-mounted attachment (as compared to rotary cutting implement) creates a very tight fit under the platform with limited ground clearance. Further, the low-profile of the tractor provided minimal ground clearance for the flail to follow the terrain. As a result, the entire tractor body was raised (via axle spacers) to allow additional clearance for the front mounted flail over undulating terrain. The standard turf-tread traction drive tires were also replaced with tractor-lug tires to provide extra traction and ground clearance.

Since, the flail cutting implement throws the grass towards the back as against a rotary implement that throws to the side, a shield was added behind the flail deck to prevent debris from wrapping around the 4WD driveshaft. Under-body transmission oil filters are re-positioned and guards were added due to minimal ground clearance. A quick-attach design was created to simplify flail installation. Additionally, a front-end hitch system was created to allow the tractor to "pull" a field cultivator by going in the reverse direction, Cowbot design and mechanical modifications ensure satisfactory performance and robustness in the field. It has sufficient power, energy, maneuverability, and traction to complete its objectives on the rough and challenging terrain on cow pastures. A drawback to Cowbot's design identified during large-scale field experiments is that the compact wheelbase and tall profile can create high degrees of pitch and roll over the rough terrain.

B. Autonomous Operation

Cowbot can operate in both manual and autonomous modes. In the manual mode, it is controlled by the traction pedal and steering wheel. In the autonomous mode, it receives steering and traction commands through CAN messages from the onboard computer. In this subsection, we present the details of these two modes and the switching protocol between them.

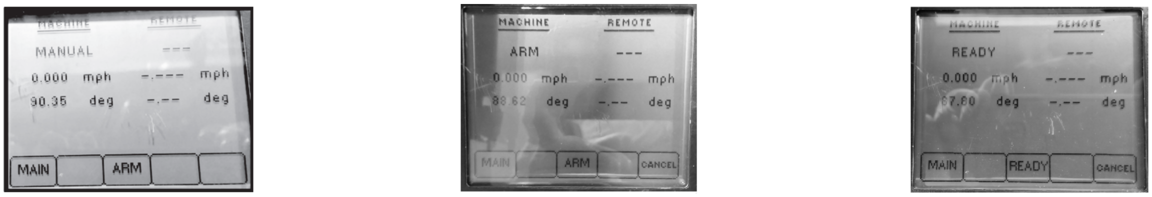
For safety considerations, Cowbot's autonomous mode is designed to be initiated by a human (operator). This is achieved by a manual to autonomous mode hand-off protocol. Cowbot has 4 operating states/modes: Manual, Arm, Ready and Auto. When autonomous operation is desired, the operator sets the Cowbot to Arm mode by pressing the arm button on the console. In Arm mode, the electronic steering system is activated, Cowbot states are recorded, the three onboard (wired) E-stops and the wireless E-Stop need to be enabled (to make sure the machine can be stopped any time for safety). Once the Cowbot is ready, the operator initiates the transition to Ready state by pressing the Arm button again. Ready state is solely a transition state and means the Cowbot is ready to operate autonomously. Cowbot will stay idle in this state waiting for the onboard computer to send a mode command for Auto mode. On receiving the Auto in the mode command from the computer, Cowbot transitions to Auto mode. The operating mode of Cowbot and the computer are sent as identical messages on the CAN bus. Both systems must indicate that their mode is Auto or the Cowbot will revert to Manual mode. If either system stops sending the message, a bus timeout error will cause the Cowbot to revert to Manual mode.

Cowbot uses a GPS-based point to point inertial navigation system and is equipped with two multi-band RTK GNSS receiver units (SwiftNav Duro Inertial) with inbuilt IMU sensors to provide high accuracy location and heading estimates. It is also equipped with front facing imaging sensors that includes two RGB-D cameras (Intel RealSense D455) and a lidar sensor (Velodyne Puck VLP-16). The perception stack of the Cowbot that aims to build capability for visual inertial navigation and weed detection on the field is currently under development. The sensors connect to an onboard computer (Dell Precision 7530) that runs the navigation software. The navigation software on Cowbot has a three-layer architecture. The top and middle layers execute on the computer and the bottom layer executes on a programmable logic controller (TORO PLC model # - Tec 5004) that controls the traction and steering systems discussed in Section I-A. The top layer is the perception and planning layer that takes input from the user and on-board sensors, and plans paths for the mower. The middle layer comprises of high level control modules for point to point navigation. It communicates with the top layer over the Robot Operating System (ROS) and takes as input the waypoint path computed by the planner. It generates steering and speed commands for the bottom layer. The middle and bottom layers communicate using CANBUS messaging protocol. When in the Auto mode, the navigation command is sent from the onboard computer via CANBUS. The command must be sent at a periodic rate so that a message timeout can be detected which would cause Autonomous operation to cease and switch into the manual mode. The Navigation Command includes desired traction speed, desired steering angle, desired motor operation speed (discrete levels) and operation commands including lift or lower for the cutting implement and PTO to turn the cutting implement on. The CANBUS interface allows full operational control of the Cowbot while relying on the electrical subsystem discussed in Section I-A for the low level control of the Cowbot's components.

C. Safety Systems

Cowbot is designed to autonomously operate large weeding implements in challenging terrain on cow pastures. Safety of operation is of primary concern in its development and a variety of operational safety systems have been implemented in the design.

- Operational Procedure: Unlike many existing agricultural robotic platforms, Cowbot qualifies as heavy machinery due to its size and power. Additionally, the intended operational environment in dairy farms is shared with livestock and human workers. In the current stage of development and agricultural autonomy, we think it is essential for a human operator to be aware that a large autonomous robot is operating on the pasture. To enforce this, we require that an operator initiates Cowbot's transition to Autonomous operating mode. As detailed in section I-B, the operator must go through a multi-step state transition process to enable Autonomous mode on the Cowbot.
- Bump Sensors: Cowbot is surrounded with force-activated bump sensors on all sides. In the event that the Cowbot runs into an obstacle, the bump sensor will activate and signal the motor controller to stop the motor. This will cause all hydraulics to deactivate and completely stop the machine.
- Flail Guard: As mentioned earlier, Cowbot is equipped with a flail-deck cutting implement to cut weeds. Further,



(a) Manual mode

(b) Arm mode

(c) Ready mode

Fig. 2: Operator console view showing different operating modes of the Cowbot.

the flail implement is custom mounted to achieve a 20 cm height of cut. In case of the standard mount position of the flail-deck at around 10 cm height of cut, the ground clearance is sufficiently low to prevent objects on the ground to be thrown to the front by the spinning flail blades. However, in the case of Cowbot, a flail guard is deployed in the front of the deck by making a curtain of heavy chains that obstruct any objects picked up by the spinning blades to be thrown to the front.

- Flashing Lights: When operating in Autonomous mode, a bright flashing beacon light mounted on top of the Cowbot turns on to attract attention and give a clear warning sign to the viewer.
- Wired E-Stop Switches: There are three wired one-press E-Stop switches on the Cowbot mounted in the front, back and on the operator console on the right side of the Cowbot. To initiate Auto mode, all E-stops must be active. In the event of unintended operation, an emergency stop can be initiated by a human (operator) by pressing and engaging any of the three E-stop switches. On pressing an E-stop switch, Cowbot will be powered off and the motor will stop operating to completely disable its operations. Each of the E-stop switches must be disengaged to power on the Cowbot again.
- Wireless E-Stop Switch: A one-press wireless E-Stop switch is also provided with the Cowbot to allow a human (operator) to stop it remotely when in Autonomous mode. It communicates with the Cowbot on the 2.4 Ghz band. The Cowbot will transition to autonomous mode only if the wireless E-Stop is turned on and remote connection is established. When the wireless E-Stop switch is engaged, Cowbot's controller will turn off the motor and exit Autonomous mode. This implementation is intended to ensure that the Cowbot can be safely and reliably disengaged when needed. In the case that the wireless E-Stop goes out of range of the Cowbot when it is operating in Autonomous mode, Cowbot will failsafe - the controller will turn off the motor and exit Autonomous mode. The wireless E-Stop must be disengaged before the Cowbot can be powered on again.
- Failsafe to manual: Potential usecase for Cowbot includes a human operator sitting on the tractor but operating in autonomous mode. In this case, to allow easy control of Cowbot in case of undesired behavior in Auto mode, any input on the traction pedal or steering wheel triggers failsafe behavior and transitions the Cowbot state to Manual. The Cowbot seat is also connected to a switch and an operator can be in or out of the seat, but a change of state in Auto mode triggers the switch and transitions the Cowbot state to Manual.

D. Solar Charging Trailer

Weed removal on large dairy farms requires sustained operations over multiple days and availability of recharging infrastructure on the farm to recharge the Cowbot. For this reason, we designed a solar-powered charging trailer to recharge Cowbot's batteries and allow it to be stationed on a farm over multiple days. In this subsection, we present the design of the charging trailer that allows off-the-grid charging for Cowbot. It is designed to fully enclose the Cowbot and is also used to transport the Cowbot over large distances between remote pastures. The solar-powered trailer can be deployed on the pasture and provides a level-2 charging terminal to charge Cowbot's batteries. Fig. 3 shows the outside and inside views of the charging trailer. The trailer is a tandem axle, V-nose trailer (Stealth Enterprises) and measures 4.3 m x 2.1 m. Cowbot's canopy was redesigned to fold-back to allow entrance into the enclosed solar charging trailer for transport.

An important prerequisite to design an off-grid solar-powered charging system is to determine the power and energy requirements of the electrical load and how long the energy storage system must supply that load without sunlight. In our application, load is the autonomous mower's battery pack that comprises $\sim$29 kWh of energy when fully charged. Ideally, the trailer and mower batteries would be recharged daily. Based on the average solar insolation in central Minnesota during the summer months (4.5-4.9 kWh/m^2/day [1]), a solar array of about 3.1 kW is required to meet the daily load (source, reference). We use ten solar panel modules (GCL-6P/72) of 325 Watt power rating to provide a 3.25 kW array needed to satisfy the load requirement. Each panel measures 1956 × 992 × 35 mm in size and weighs 22.2 kg. Area on the roof of the trailer can only fit four panels. For this reason, we opted for a design with retracting brackets that extend over the sides of the trailer to mount the panels. The mounting bracket is designed and attached to the trailer roof to hold four fixed panels. Under the fixed panels, there are two lower rows of three panels each that are mounted on fully extending, heavy-duty, drawer slides. It allows each row to slide out to access sunlight, one to the left side of the trailer and the other to the right side. When in transportation, the two rows are retracted under the fixed panels.

To design the trailer battery system we considered multiple factors including the degree of discharge (DoD) on trailer

(a) Solar-charging trailer (b) Trailer Electricals

Fig. 3: The inside and outside view of the solar panel trailer.

and mower batteries, trailer towing weight and budgetary restrictions. There is an inverse relationship between DoD and battery life: allowing batteries to discharge more, reduces the number of charge/discharge cycles of the battery. A DoD of 35% was selected as a reasonable compromise between mowing capacity, battery life and reserve capacity, leading to a daily recharging load for the trailer battery pack of 18.9 kWh based on practical experiments. We use eight 6v 375 Ah deep-cycle lead acid batteries (model: Trojan SAGM 06 375 solar batteries) connected in series to make a 48 volt battery pack with a combined storage capacity of 18.3 kWh. Each battery weighs 52 kg resulting in a total battery pack weight of 416 kg.

The panels are wired as five parallel pairs of two panels each in series. Paired wiring connections lessen the overall impact of shading on individual panels and keeps the resultant voltage and current within the input specifications of the charge controller that manages the battery charging process. The solar panel output wires are fused in a combiner box which feeds directly into an 80 Amp charge controller (AIMS SCC80AMPPT). DC output from the battery pack is wired to a 6 kW power inverter (AIMS PICOGLF60W48V240VS) which converts it to AC and feeds the load center to be distributed to any AC loads. The AC loads comprise 120V outlets and a 240V Level 2 electric vehicle charger (Clipper Creek LCS-30-C12-L25-53) that provides a 24 Amp/5.8 kWh charging terminal via a J1772 connector.

II. Planning and Control

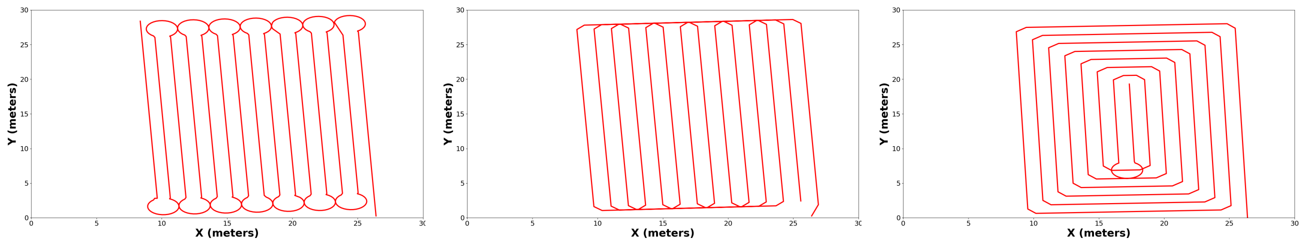
A. Coverage Path Planning

To mow weeds on the pasture we compute coverage paths for the Cowbot. A path planner for the Cowbot must ensure that the entire pasture is covered and the path length is minimized. However, there are additional considerations when operating on challenging terrain in cow pastures. In the presence of hills and slopes on the pasture, it is safer to drive up and down the slope rather than across the slope due to the risk of toppling of the vehicle. Further, the space needed to turn around the vehicle near the boundary of the pasture, also called headland or turn areas, can create challenges to ensure coverage and adds overhead to the length of the path. For this reason, we present multiple path planners that may be used in different environments and conditions.

1) Adjacent Row Path Planner: Paths computed by adjacent row path planner comprise of adjacent to-and-fro passes across the length of the field in alternating directions. The width of each pass is equal to the width of the mowing implement on the mower. This path pattern is also known as boustrophedon or lawn mower pattern. It is the most common pattern used in mechanical mowing as it allows an operator to mow straight lines by following the contour of the previous pass. Since consecutive passes are adjacent to each other, the mower must make a sharp turn at the end of each pass to move to the next pass. As the turn diameter of Cowbot is larger than the distance to the next pass (width of the cutting implement), additional space (headland) is needed at the two ends of the field for the Cowbot to turn around and move to the next pass. This is a very common scenario with farm vehicles and there exists a body of literature [2] that focuses on minimizing the width of the headland using various turning maneuvers like fishtail and lightbulb (also called omega) turns. In our implementation we use light-bulb turns at the end of each pass to move to the next pass.

2) Skip-Row Path Planner: Similar to the adjacent-row planner, the skip-row planner also comprises of to-and-fro passes across the length of the field in alternating directions. However, unlike the adjacent-row planner, it does not require consecutive passes to be adjacent and allows the Cowbot to skip rows between consecutive to-and-fro passes on the coverage path. It plans paths for the Cowbot such that the distance between consecutive passes is more than the turn diameter. This allows the Cowbot to turn around to move the next pass without needing additional space at the end of the pass. Our implementation of the skip row planner admits multiple rows between passes allowing 90° sharp turns and reduces the width of the required headland to the minimum space needed for the Cowbot to traverse (equal to the width of the cutting implement). Even though the skip-row planner reduces the width of the headland at both ends, the length of the path traversed when moving between passes adds to the overhead as it repeatedly mows on the same area and does not contribute to coverage.

3) Spiral Path Planner: The spiral path planner computes a path for the Cowbot that starts along the boundary of the pasture and gradually moves inward in a spiral pattern. The path starts by following the perimeter of the pasture. At the end of a round of the spiral path, the planner shrinks the size of the pasture along each edge to remove the covered area from consideration. To compute the new perimeter, each edge of the pasture is moved inward by distance equal to the width of the cutting implement. Subsequent round of the spiral path follows the new perimeter that encloses the uncovered area. The spiral planner terminates when the uncovered area on the pasture shrinks to zero. A spiral path does not revisit any location on the pasture. It removes the need for headlands and does not add any overhead on path length. This allows the spiral planner to be most efficient in terms of total path length amongst the three planners. However, in the case of slopes and hills on the cow pasture, path computed by the spiral planner may not be feasible for the Cowbot. This is because traversing across slopes is not recommended for larger farm vehicles like Cowbot as it can lead to toppling of the vehicle. Spiral planner requires the Cowbot to traverse in all directions over the course of the planned path and hence is not well-suited for slopes.



(a) (b) (c)

Fig. 4: Figures show sample paths planned by the three planners: (a) adjacent-row path planner (b) skip-row path planner (c) spiral path planner

4) A note on irregularly shaped pasture coverage: Cow pastures can comprise large tracts of land and have different local features even within the same pasture. In our field evaluations we found that dividing a pasture into smaller fields by topography allows the use of the most-suitable planner for each field. There are a number of cellular decomposition methods in the literature that may also be used for dividing a pasture into smaller fields. We refer the interested reader to those papers for details on such methods. We restrict our division of the pasture to convex polygon shaped fields. The use of adjacent-row and skip-row planners in a convex polygon shaped field is straight-forward. Identify the longest edge of the field and plan all passes on the path to be parallel to it. The length of each pass is determined by the intersection of the pass with the two edges of the field on either side minus the width of the headland at each end. The spiral planner does not require any modification. It starts by following the perimeter of the field. At the end of the first round of the spiral path, it computes a new perimeter of the field that comprises only the uncovered area by moving all edges towards the interior of the field by distance equal to the width of the cutting implement. The path then follows the new perimeter to compute the next round of the spiral. The planner iterates this process to compute subsequent rounds of the spiral path and terminates when the uncovered area of the field shrinks to zero.

B. Kinematic Model

In this section we develop a geometric model for Cowbot's kinematics. Cowbot is built on a four-wheeled rear steered platform with traction on the front two wheels. To design a navigation controller for the Cowbot, we need to model its kinematics. In previous work, Rajamani [3] designed a geometric model for vehicles with independent steering control on both front and rear wheels, and described its extension to front steered vehicles. Since a rear steered vehicle turns opposite to the steering angle direction, there are important differences from Rajamani's vehicle model. We extend their model to rear steered front wheel drivetrain vehicles and derive the associated kinematic equations. We use a bicycle model to represent the four wheeled robot (similar to [4] and [3]) where the front two wheels and the rear two wheels are each represented by a single wheel at the front and rear of the bicycle model, respectively. The robot is assumed to operate in the two dimensional plane with zero slip at either of the two wheels. The zero slip assumption is standard in the literature [3] and holds true at low speeds.

Consider the top view of the bicycle model shown in Figure 5. The front wheel of the model is centered at $\mathcal{F}$ and the rear wheel is centered at $\mathcal{B}$. Wheel base of the bicycle model is of length L. The robot moves with a speed v with heading angle θ about the positive x-axis. The velocity at each of the wheels is in the direction of motion of the wheels and is shown in the figure with dashed arrows. Steering angle of the rear wheel, δ, is measured with respect to the longitudinal axis of the robot model. Both, heading and steering angles of the model are measured in the counter clockwise direction. As shown in the figure, the robot turns in the direction opposite to the steering angle of the rear wheel. This is because the instantaneous center of rotation (ICR), found as the intersection of the rotation axes of the front and rear wheels, is located on the opposite side at $\mathcal{I}$ resulting in an angular velocity in the direction opposite to the rear wheel steering angle.

We consider a 3-tuple state for the bicycle model, $< x, y, \theta >$. Here (x, y) are the location coordinates of a fixed reference point on the model and θ is the heading direction of the bicycle. The inputs to the model are the magnitude of the velocity, v, and the steering angle of the rear wheel, δ. The choice of reference point may be driven by the application. For instance, in the case when a sensor or actuator is mounted in the front of the robot, the center of the front wheel of the bicycle would be an obvious choice for the reference point. Other applications might require the rear end or another point on the robot to be tracked as the reference point. In the following, we consider three reference point locations on the model and derive the kinematic equations for the bicycle model at each of these points.

1) Reference point at the center of gravity: Consider the bicycle model geometry in Figure 5 that shows the reference point location at the center of gravity of the bicycle model. Let the coordinates of the reference point be $\mathcal{C} \equiv (x_c, y_c)$. On the four wheeled robot, this point corresponds to the center of gravity on the longitudinal axis of the robot. The direction of motion at $\mathcal{B}$ is at an angle $\boldsymbol{\beta}$ with respect to the longitudinal axis. $\boldsymbol{\beta}$ is called the slip angle. To derive the state gradient equations for the bicycle model, we consider $\triangle\mathcal{FIC}$ and $\triangle\mathcal{FIB}$. The slip angle $\boldsymbol{\beta}$ at the reference point $\mathcal{C}$ can be

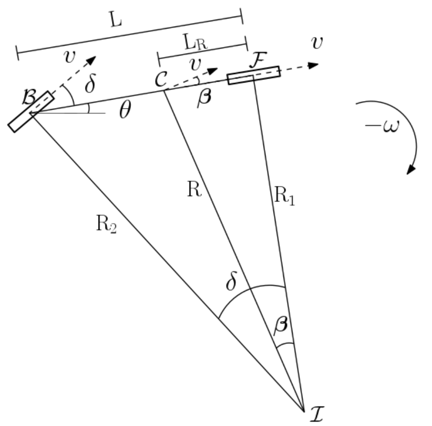


Fig. 5: Bicycle model for a rear steered vehicle with front wheel drivetrain. The figure shows the steering geometry when the reference point is located at the center of gravity of the robot ($\mathcal{C}$).

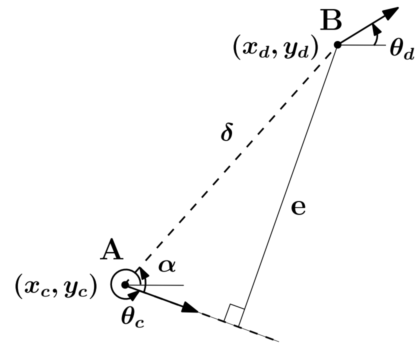


Fig. 6: Engagement geometry for Cowbot's geometric path following controller.

calculate as follows:

$$\tan\delta = \frac{\mathrm{L}}{\mathrm{R}_1} \quad \Rightarrow \quad \mathrm{R}_1 = \frac{\mathrm{L}}{\tan\delta} \tag{1}$$

$$\tan\boldsymbol{\beta} = \frac{\mathrm{L_R}}{\mathrm{R}_1} \quad \Rightarrow \quad \mathrm{R}_1 = \frac{\mathrm{L_R}}{\tan\boldsymbol{\beta}} \tag{2}$$

Using equations (1) and (2),

$$\frac{\mathrm{L}}{\tan\delta} = \frac{\mathrm{L_R}}{\tan\boldsymbol{\beta}} \quad \Rightarrow \quad \boldsymbol{\beta} = \arctan\left(\frac{\mathrm{L_R}}{\mathrm{L}}\tan\delta\right) \tag{3}$$

The turn radius R at the reference point $\mathcal{C}$ may be calculate using equation (1) as follows:

$$\cos\boldsymbol{\beta} = \frac{\mathrm{R}_1}{\mathrm{R}} \quad \Rightarrow \quad \mathrm{R} = \frac{\mathrm{R}_1}{\cos\boldsymbol{\beta}} = \frac{\mathrm{L}}{\tan\delta\cos\boldsymbol{\beta}} \tag{4}$$

We can now write the equations for the state gradient as follows:

$$\dot{x} = v\cos(\theta + \boldsymbol{\beta}) \tag{5}$$

$$\dot{y} = v\sin(\theta + \boldsymbol{\beta}) \tag{6}$$

$$\dot{\theta} = -\omega = -\frac{v}{\mathrm{R}} \;=\; -\frac{v}{\mathrm{L}}\tan\delta\cos\boldsymbol{\beta} \tag{7}$$

C. Navigation Controller Design

In this section, we present the design of the lateral control law deployed on the Cowbot for path-following. Cowbot uses a geometric path-following controller for steering control. We refer to the controller as *Cowbot* control law. The Cowbot control law is suitable for tracking curved paths and provides global convergence to the reference trajectory from any starting location. It combines the requirements to align robot heading with desired heading, eliminate cross-track error and keep the steering angle within the maximum steering limits.

We show the engagement geometry for a wheeled mobile robot with a finite turning radius tracking a reference point in figure 6. The robot is represented using a point mass located at its geometric center. The figure shows the robot's current location, $A \equiv (x_c, y_c)$, and heading angle, θ_c. The desired location and heading angle on the reference trajectory for the robot are shown as $B \equiv (x_d, y_d)$ and θ_d respectively. We define the heading error, $\phi \in [-\pi, \pi]$, as the angular difference between the current heading and the desired heading with respect to the current heading. The cross-track error, $\mathbf{e} \in \mathbb{R}^+$, is the shortest distance to the desired location from the direction of travel of the robot. We also define LOS (Line-of-Sight) distance, $\delta \in \mathbb{R}^+$, as the euclidean distance between robot's current and desired locations and LOS angle, $\alpha \in [-\pi, \pi]$, as the angle that the LOS line (**AB**) makes with the robot's heading direction. We note from Figure 6 that

$$\sin\alpha = \frac{\mathbf{e}}{\delta} \tag{8}$$

The Cowbot lateral controller steers the robot to drive both cross-track error and heading error to zero. The steering angle, ω, is assumed to lie in the range $[\omega^-, \omega^+]$, where ω^- and ω^+ are the minimum and maximum steering angles of the robot, respectively. The control law is expressed as:

$$\omega = k_p\alpha + k_h\frac{\phi}{\max(c, \delta)} \tag{9}$$

where, c is a small finite constant, k_p is the proportional gain and k_h is the heading gain. The Cowbot control law has two components. The first component is a proportional controller that steers the robot to bring the LOS angle to zero. It directly affects the cross-track error. The second component is proportional to the heading error and inversely proportional to the LOS distance. When the robot is farther away from the reference point, the inverse proportionality to LOS distance makes the first component of the control law dominant. As the robot nears the desired location, the second component ensures that the robot heading is aligned with the desired heading angle. c ensures a finite value in the denominator of the second component. We fix the value of c to be equal to the distance tolerance. Thus, when $\delta == c$, the desired location is moved to the next point on the reference trajectory. Value for k_p and k_h are determined experimentally.

$$\omega = k_p\sin^{-1}\frac{\mathbf{e}}{\delta} + k_h\frac{\phi}{\max(c, \frac{\mathbf{e}}{\sin\alpha})} \tag{10}$$

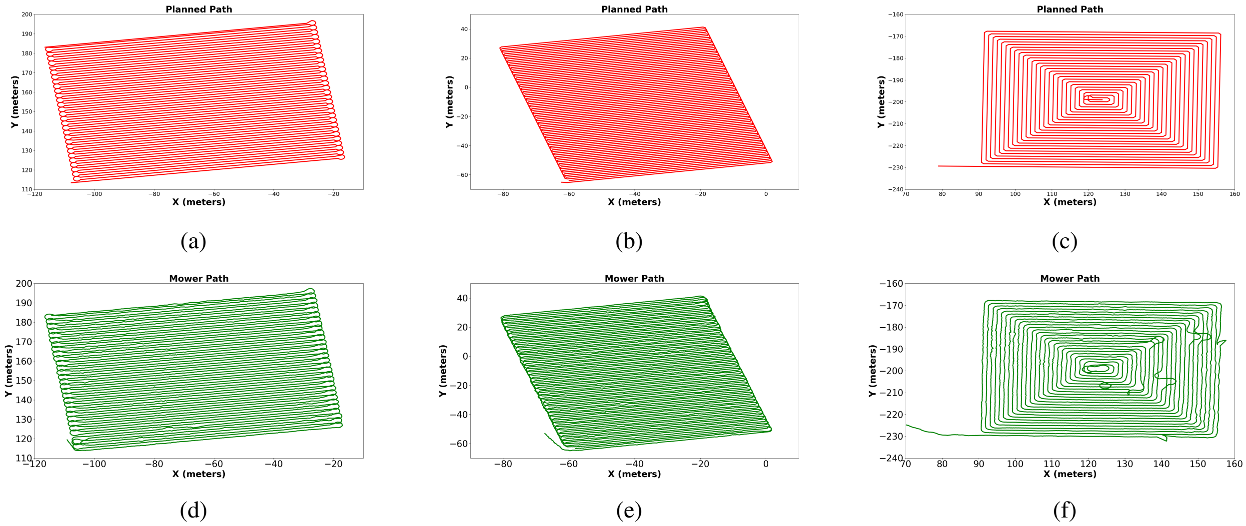


Fig. 7: Figures show paths planned by the three planners and the actual paths followed by Cowbot. Adjacent-Row Path Planner: (a) planned (d) actual; Skip-Row Path Planner: (b) planned (e) actual; Spiral Path Planner: (c) planned (f) actual

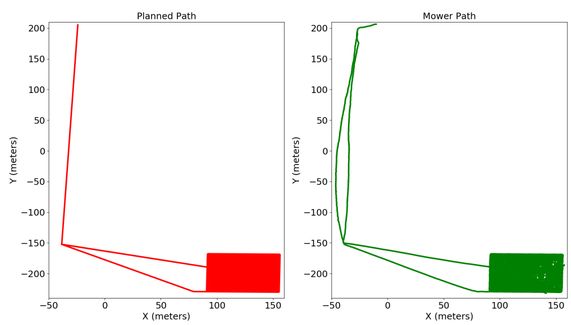


Fig. 8: Spiral path showing the return to home functionality of the Planner.

III. Field Evaluation

Cowbot was tested through an extensive field evaluation procedure covering 6 adjacent 1-acre cow pastures in Morris, Minnesota. During the field experiments, all 3 coverage path planning algorithms discussed in II-A were tested in separate 1-acre pastures. Remaining 3 pastures were mowed by a human operated pasture mower as the baselines. The test pastures presented a rugged environment to Cowbot as well as dense and large weed populations. The navigation controller presented in II-C was developed and tuned to make the Cowbot safely and successfully navigate in environments with varying topography including grasslands, cow pastures, hills, valleys with dense weed populations and rough terrain. In addition to large scale field experiments in 1-acre cow pastures, Cowbot was also tested at night. Cowbot was able to complete its operation successfully and mow the designated area without human intervention at night. Night experiments have demonstrated that the proposed autonomous weed control platform is able to operate without daylight, using GPS signal for its navigation system.

Planner Name	SoC at Start	SoC at End
Adjacent Row Path Planner	93	39
Skip Row Path Planner	96	37
Spiral Path Planner	71	36

TABLE I: State of Charge (SoC) for each experiment run showing the total energy consumed in percentage.

Field evaluations show that Cowbot is a suitable platform for mowing weeds on pastures with difficult to navigate rough terrain and our presented coverage path planners working together with our control algorithms are well suited for the task in terms of operational and computational efficiency on real-time systems.

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