2019 Project Abstract
For the Period Ending June 30, 2024

PROJECT TITLE: Agricultural Weed Control Using Autonomous Mowers – Phase 2
PROJECT MANAGER: Eric Buchanan
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 08g as extended by M.L. 2022, Chp. 94, Sec. 2, Subd. 19 (c.1) [to June 30, 2023] as extended by M.L 2023, Chapter 60, Article 2, Sec. 2. Subd. 18

APPROPRIATION AMOUNT: $900,000
AMOUNT SPENT: $899,858
AMOUNT REMAINING: $142

Sound bite of Project Outcomes and Results
An autonomous robot – the Weed Terminator - was successfully developed and demonstrated to control weeds in corn fields. Widespread adoption of the "Weed Terminator" could reduce agriculture carbon footprints, eliminate harm from herbicide runoff, and control resistant weeds.

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. 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 developed improved methods using solar powered robots to control weeds on agricultural lands. Testing focused on weeding within row crops such as corn and soybeans. Specifically:

- Purchased a small robotic test vehicle from Rover Robotics for testing navigation and weeding concepts
- Purchased a robotic vehicle (Thorvald) from Saga Robotics as the base for a weed hunting robot
- Designed and built a carbon fiber frame to configure the Thorvald for corn fields
- Designed and built various weed control implements including lasers and cutting tools
- Developed software using the global positioning system (GPS) for navigating in corn fields
- Tested a robotic weeding system in corn fields and publicly demonstrated the system at Farmfest

This project provides a glimpse of a future where farmers can produce food, fuel, and fiber while decreasing negative impacts on the environment. Over the last few decades farms have gotten larger as farmers acquire more land to remain profitable in the face of shrinking margins. Farming equipment has gotten larger to keep pace with larger farms -- seeking to increase the productivity of a single driver. While more work is needed, this project has demonstrated that removing the need for a driver allows for different solutions; solutions that can reduce harm to Minnesota's agricultural environment while keeping farmers productive and profitable.

Project Results Use and Dissemination
The Weed Terminator robot was actively demonstrated several times each day in a corn plot at Farmfest. Farmfest is a large state-wide farm show which was held from August 1-3, 2023. The Weed Terminator was also included in presentation material and actively demonstrated at the Midwest Farm Energy Conference held in

Morris, MN, June 26th and 27th, 2024. The Weed Terminator was also featured in a segment of "The Prairie Sportsman", a production Pioneer Public Television. The segment aired on April 28, 2024.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2019 ENRTF Work Plan Final Report (Main Document)

Today's Date: January 9, 2025

Final Report

Date of Work Plan Approval: June 17, 2019

Project Completion Date: June 30, 2024

PROJECT TITLE: Agricultural Weed Control Using Autonomous Mowers – Phase 2

Project Manager: Eric Buchanan

Organization: University of Minnesota

College/Department/Division: West Central Research and Outreach Center

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Location: Statewide

Total Project Budget: $900,000

Amount Spent: $899,858

Balance: $142

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 08g as extended by M.L. 2022, Chp. 94, Sec. 2, Subd. 19 (c.1) [to June 30, 2023] as extended by M.L 2023, Chapter 60, Article 2, Sec. 2. Subd. 18

Appropriation Language:

$900,000 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.

M.L. 2022 - Sec. 2. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2023]

M.L. 2023 - Sec. 2. Carryforward; Extensions [to June 30, 2024]

I. 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 second 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,

The project team will develop and test a robotic weed hunting system to control weeds in mid to late term row crops. A weed hunter robot will be more technically advanced than the phase 1 pasture mowing and early term crop robots requiring additional engineering, navigation and visual identification hardware and software development, and testing. The phase 2 electric powered robot will be autonomously recharged by a portable solar PV charging station installed on a cargo trailer. Safety protocols will be developed and tested. The weed hunter robot will then be field tested 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.

II. OVERALL PROJECT STATUS UPDATES:

First Update March 1, 2020
The project engineer position for this project was advertised, interviews were conducted, and an offer letter has been extended. A small, commercial robotic platform has been purchased for testing weed control prototype implements. A request for proposal has been initiated with the University purchasing department for the procurement of a robust vehicle to be adapted for hunting and killing weeds in row crops.

Second Update September 1, 2020
10/26/20 End date extension is pending legislative action.

Initial field testing of a Rover Robotics test vehicle was done to gather a first look at video data from a corn field. An RFP was released for a robotic vehicle to be used as the final platform for weed control implements. A project engineer was hired and a first weed control prototype was tested.

Third Update March 1, 2021
A SAGA Robotics Thorvald robot has been purchased for a fourth quarter delivery. Several weed control implement strategies have been identified for prototype testing. Several components have been purchased to facilitate the testing.

Fourth Update September 1, 2021
Progress continues with the development and testing of weed control prototypes. The most promising ideas are being tested on a push cart that was built to mimic the final robot configuration. A three camera and shading module has been built and mounted to the pushcart to collect video of corn and weeds in an organic field to aid in the development of an algorithm to identify weeds.

Amendment Request as of September 20, 2021
We are requesting funds be shifted from the Professional/Technical/Service contracts line to a new line in the Other budget to account for a new software license.

- $4800 are being reduced in the budget from Professional/Technical/Service contracts bringing it to $10,200.
- $4800 are being added to the Other category under a new line for software bringing the total to $21,481.

A license for SolidWorks computer aided design (CAD) software is needed to design robot vehicle and weed control parts. The University only has a license for student use which excludes research. This amendment will have no effect on any task deliverables.

Amendment Approved by LCCMR 10/21/2021

Fifth Update March 1, 2022
The Saga Robotics Thorvald vehicle will be ready to ship by the end of March and should be in our possession in April. A frame for the robot has been designed to allow the Thorvald to operate in a late term corn field while holding the selected weed control devices. The project is on schedule to begin field testing this summer.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
The Saga Robotics Thorvald vehicle ship date was further delayed but did arrive in Minneapolis on July 3rd. However, there were issues getting it through customs which further delayed its arrival at the WCROC until July 21st. Weed terminating implement designs have been selected and a robot frame has been designed. Frame components have been ordered and delivered. Work continues on navigation and weed identification using smaller remote controlled robotic platforms.

Amendment Request as of September 15, 2022 #1
We are requesting a no-cost extension of the project for one year making the end date June 30, 2024
The targeted window for application of the weed terminator in corn fields is during the month of July. This is when corn plants have matured enough that field work with traditional tractors ends but the corn canopy has not yet closed to slow weed growth. Since the Thorvald robot did not arrive until the end of July and the project is scheduled to end next June there will not be a chance to test the Weed Terminator during the desired corn growth stage. No budget changes are required to extend the project.

Amendment #1 pending further LCCMR and legislative action as of 10/6/2022
Amendment #1 approved by legislature and signed into law 5/24/23

Amendment Request as of September 15, 2022, #2
We are also requesting funds be shifted from the Capital Expenditures line to the Equipment/Tools/Supplies line.

- $13,380 are being reduced in the Capital Expenditures budget leaving a total of $130,000.
- $13,380 are being added to the Equipment/Tools/Supplies budget bringing the total to $64,299.

Funding was originally included in Capital Expenditures for a Rover Robotics platform to use for preliminary testing of sensor set-ups and control software, but we purchased the same robot under a previous grant and can

reuse it instead of purchasing a new one. The funds will instead be used for equipment, tools, and supplies to build the new Weed Terminator robot.

Amendment #2 Approved by LCCMR 10/6/2022.

Seventh Update as of March 1, 2023:
A carbon fiber frame was fabricated and attached to the SAGA Thorvald robotic vehicle. The frame will hold weed control implements, navigation and control hardware, and batteries to power all equipment beyond vehicle wheel motors. The design of weed control implements has been refined and the ability of a navigation controller to interface with the Thorvald operating system controlling the robot has been established. Preparations are being made to demonstrate the Weed Terminator robot at Farm Fest in August 2023.

Eighth Update as of September 1, 2023:
The first fully functioning version of the Weed Terminator was completed and tested in fields at the WCROC and at Farmfest in August. The robot worked well and garnered a lot of interest at Farmfest. We did encounter a few minor mechanical failures – some we were able to repair on site and some indicated needs for design improvements. The main lesson learned was that navigation accuracy needs to be improved beyond GPS alone. Work this winter will focus on mechanical design improvements and adding camera information to the navigation controller.

Amendment Request as of September 28, 2023
We are requesting funding be shifted from the Professional/Technical/Service contracts, Capital Expenditures, and Printing lines to the Personnel and Travel lines.

- Professional/Technical/Service Contracts would be reduced by $3,200 to a revised budget of $7,000
- Capital Expenditures would be reduced by $25,098 to a revised budget of $104,902
- Printing would be reduced by $1,316 to a revised budget of $184
- Travel would increase by $4,516 to a revised budget of $14,215
- Personnel would increase by $25,098 to a revised budget of $687,919

These changes are being requested because we have purchased all the capital hardware and contracts needed for this project, but in the 5th year of a 3 year project we need additional funds in travel and personnel to complete field testing.

Amendment Approved by LCCMR 10/31/2023

Ninth Update as of March 1, 2024
The project is winding down and preparing for follow-on work funded by the ENTRF. Remaining work involves improving system navigation accuracy by adding cameras. Weeding accuracy can also be improved by modifying the weeding implement structure to mechanically track to the center of crop rows. Autonomous robot charging was explored by a senior mechanical engineering class at the University of Minnesota.

Amendment Request as of April 29, 2024
We are requesting funding be shifted from the Equipment/Tools/Supplies, Travel, and Other budgets to the Personnel line.

- Equipment/Tools/Supplies would be reduced by $7,970 to a revised budget of $56,329
- Travel would be reduced by $965 to a revised budget of $13,250
- Other would be reduced by $396 to a revised budget of $21,085
- Personnel would increase by $9,331 to a revised budget of $697,250

These changes are being requested to move project funds that will not be spent to personnel to complete camera navigation work to set up the next phase of research. The project is in the 5th year of a 3-year project.

Amendment Approved by LCCMR 8/30/2024.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
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. 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.

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- 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.

This project provides a glimpse of a future where farmers can produce food, fuel, and fiber while decreasing negative impacts on the environment. Over the last few decades farms have gotten larger as farmers acquire more land to remain profitable in the face of shrinking margins. Farming equipment has gotten larger to keep pace with larger farms -- seeking to increase the productivity of a single driver. While more work is needed, this project has demonstrated that removing the need for a driver allows for different solutions; solutions that can reduce harm to Minnesota's agricultural environment while keeping farmers productive and profitable.

Amendment Request as of January 9, 2025
We are requesting funding be shifted from the Personnel and Travel budgets to the Equipment/Tools/Supplies, and Other lines.

- Personnel would be reduced by $388 to a revised budget of $696,862
- Travel would be reduced by $604 to a revised budget of $12,646
- Other would be increased by $279 to a revised budget of $21,364
- Equipment/Tools/Supplies would increase by $713 to a revised budget of $57,042

These changes are being requested to move project funds that were not spent to budget lines where there was a small deficit.

Amendment Approved by LCCMR 2/17/2025.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1 Title: Develop Navigation and Weed Identification Systems
Description: A weed hunting robot needs to be able to navigate between crop rows, exit one row and find the next row, as well as maneuver within a row as weeds are identified. Algorithms and sensors will be developed to accomplish this without damaging the row crops. Additionally, autonomous vehicles will need to incorporate software safety protocols to ensure safety of equipment, operators, and bystanders.

A weed hunting robot also needs to be able to identify undesirable weeds and distinguish them from desirable row crops. Several different types of sensors or a combination of sensors could be used to identify weeds including visual identification from a camera image. Multiple strategies will be considered and tested for effectiveness.

Initial testing of navigation and weed identification strategies will be done with a small robot model like the Rover Robotics 4-wheel drive robot. Testing will be conducted on the University of Minnesota campus and later in fields at the WCROC. Systems will be tested for accuracy and efficiency and refined as needed. Successful systems will then be transferred to the final robotic vehicle platform developed concurrently.

ACTIVITY 1 ENRTF BUDGET: $370,852

Outcome	Completion Date
1. Develop initial sensor/control systems	5/1/2020
2. Refine sensor/control systems with field trials	5/1/2021
3. Adapt navigation/weed ID systems to final weed hunter robot	7/1/2021
4. Performance testing of refined systems	9/1/2022

First Update March 1, 2020
Initial work is focused on determining strategies for navigating in row crops and identifying weeds. Strategies will be assessed for pros and cons to select the most promising methods for testing on robot prototypes. A Rover Robotics robot has been purchased for proof of concept testing.

Second Update September 1, 2020
The Rover Robotics vehicle was used to drive in a corn field and collect data from GPS sensors and cameras to aid in navigation and weed identification system development. Further control work awaits weed control implement development.

Third Update March 1, 2021
Cameras and mounting hardware have been purchased and are being adapted to the Rover Robotics vehicle. The Rover with cameras will be used to drive through a cornfield approximately weekly to provide a detailed video survey of how the crop and weeds appear as they develop. This data will be central to developing weed/crop identification algorithms.

Fourth Update September 1, 2021
A typical row in an organic corn field at the WCROC was selected for video documentation of weed/corn growth. A Rover Robotics vehicle was outfitted with a camera and driven down the selected row weekly to provide video for development of an algorithm to identify weeds. The vehicle proved a little difficult to drive in the field so a pushcart was built to mimic the eventual Thorvald robot which will span 3 rows. The camera was mounted to the pushcart which proved to be a more stable platform for video. Computer Science researchers were able to develop an algorithm that can identify the corn rows on either side of the camera and the ground plain. In the presence of a lot of weeds determining the corn rows proved more difficult. Currently, a three camera array (one forward, one to the side, and one to the rear) is being used with cameras that can determine depth. Additionally, it was found to be necessary to provide shading for the camera area to prevent sunlit bright spots from confusing the algorithm. Video is continuing to be collected for further development over the winter.

Fifth Update March 1, 2022
Algorithms have been developed that can process camera images from a corn row and identify the ground plane as well as two vertical planes that correspond to the centerline of each row of corn plants on either side of a row. Further processing creates a rectangle around each individual corn stalk. The created rectangles show

where the corn plants are relative to the Thorvald allowing weed control devices to operate between corn plants. More work is needed to allow faster image processing so plant identification can be done in real time.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
Software to allow navigation in a corn field using GPS has been developed and tested on a small robotics platform (Rover Robotics). Work continues developing software to identify corn plants from camera images. Identifying where the corn plants are also, by inference, indicates where the spaces are between corn plants that can harbor weeds. The initial strategy will be to deploy and activate weed cutting implements in all spaces that do not contain corn.

Seventh Update as of March 1, 2023:
Navigation software that was tested on a small robotic platform (Rover Robotics) was moved to the Thorvald vehicle for testing. The software was running on a separate onboard computer and successfully integrated with the Thorvald computer and a remote GPS station. A simple multi-waypoint navigation test confirmed the compatibility of the set-up. Current work focuses on simulation-based validation of corn-row navigation.

Eighth Update as of September 1, 2023:
Corn row navigation was validated in corn fields at the WCROC and on a corn plot at Farmfest. Row navigation was successful, but a limitation was discovered. Navigation in corn rows using GPS coordinates of the field boundary assumes the individual corn rows are straight. Unfortunately, corn rows are straight but not straight enough to stay within the cutting implement's allowable error of a couple inches. When row deviation exceeds the allowable error cutting implements can cut into the corn rows. A solution to this issue could use camera images to locate corn rows once the robot has entered a row while using GPS for overall navigation. Work this winter will focus on incorporating cameras into the navigation scheme.

Ninth Update as of March 1, 2024
Camera based navigation will be explored with simulation tools provided by SAGA Robotics for their Thorvald robot. The concept is to visually identify the location of corn rows from a video feed and use a calculated proximity from the left and right side rows to provide an error signal that can then be used to correct steering commands. This is a challenging task – especially with the remaining time and project budget – so it is being tackled with simulation tools. This should give the next phase of research a nice head start for the addition of cameras.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
Navigation and weed identification proved to be difficult tasks in a corn field. Much work was done to record video of corn plants at different growth stages in a corn field. Software was developed to identify the stalk portion of the corn plant and the ground plane. Using rectangles placed around the image of corn stalks and the identified ground plane two additional vertical planes were established containing the corn plants in the rows on either side of the robot. These vertical planes can be treated like virtual walls to aid in navigating down the center of a row. Moreover, the rectangles placed around individual corn stalks indicate a plant – not a weed – and can be used to identify weeds under the assumption that everything that is NOT a corn stalk is a weed. This early weed identification and navigation work was successful in simulation, but the onboard processor on the robot could not process images fast enough to be practical.

Navigation was limited to RTK GPS. GPS is global positioning using satellites and a receiver to establish your location. Accuracy of a GPS system can be greatly improved by adding a base station which is a stationary tripod

holding a satellite receiver in addition to the receiver on the robot. Computer software uses data from the robot receiver and the base station receiver to triangulate a more accurate location – potentially accurate to less than an inch. Even with a base station the GPS navigation system struggled to keep the robot in the center of a row. Without camera identification of weeds, spring-loaded cutters were used to cut weeds right up to the corn stalks by bouncing off them. Because corn rows are not planted precisely straight, deviations from the row center sometimes resulted in damage to the corn plants.

The final solution was to install software operating an 'expert' navigation protocol. In this scheme an operator manually drives a vehicle where desired and software records GPS coordinates along the way. After a little processing the system can then drive the recorded path autonomously. This proved successful for demonstrations but is not a long-term solution because an operator is needed to drive the whole path. Promising simulation work using cameras was completed at the end of the project and will be incorporated in the next phase of research.

ACTIVITY 2 Title: Weed Control System Development
Description: A weed hunting robot needs a means to kill identified weeds. Several methods are possible and will be considered including spot spraying of an herbicide, mowing/cutting, and root destruction (hoeing/pulling). Potential weed destruction methodologies will be assessed for their suitability using several factors including potential effectiveness, robot power requirements, safety, acceptability in organic fields, robustness of mechanisms, and control difficulty. Top contenders will be prototyped and tested on a small robot model like the Rover Robotics 4-wheel drive robot.

A final design will be selected and fabricated for testing on the final robotic vehicle platform developed concurrently.

ACTIVITY 2 ENRTF BUDGET: $136,946

Outcome	Completion Date
1. Develop matrix of weed control strategies and suitability factors	10/1/2019
2. Develop/test selected weed control strategy prototypes	8/1/2020
3. Select final weed control strategy(s)	10/1/2020
4. Performance testing of refined systems	9/1/2022

First Update March 1, 2020
Efforts have centered around finding and hiring a project engineer to manage this activity. A job description was written and disseminated through the University HR office as well as being advertised in local media. Initial applications were narrowed to three for interviews. An offer letter has been extended with an expected start date in mid-March.

Second Update September 1, 2020
A project engineer has been hired and started work in March. A weed control matrix has been developed and a weed control prototype similar to a small tiller has been developed. An initial test of the tiller prototype has been conducted using the Rover Robotics test vehicle with promising results. Two other options are being prototyped for field testing.

Third Update March 1, 2021
Three to five weed control possibilities have been identified for two field areas: intra-row and inter-row. Intra-row refers to weeds that grow between crop plants in-line with the crop row. Intra-row weeds are generally not controlled by typical mechanical weed control strategies like cultivators. Inter-row weeds are those that grow between crop rows and are generally controlled with mechanical cultivators. Several components have been purchased to facilitate a first level of prototype testing. This first level of testing is a quick and dirty test that will

just determine if the control method can kill weeds. Passing the first level will lead to further prototype work to provide a more quantitative assessment including energy usage. This second level of testing will provide data that can be used to select the final ideas for use on the actual field robot.

Fourth Update September 1, 2021
Several ideas for controlling intra- and inter-row weeds were developed and bench tested to determine their plausibility for operation on the final robot. For inter-row weeds the leading candidate is a commercial weed trimmer head with a solid blade (as opposed to a string trimmer). Two Stihl brand weed trimmers were purchased and will be modified to fit the robot and be controlled by the robot operating system.

For intra-row weeds, a CO2 laser was purchased with an optical focusing lens and mounted to the push cart. It was hoped the laser could cut weeds between corn plants by simply being turned on and off to miss corn plants as the robot moved slowly down a row. It is desirable to avoid stopping and starting the robot to deal with intra-row weeds. It turned out that there were too many weeds for the laser to cut fast enough. Calculations for a more powerful laser suggested the battery power requirements would be too great to be practical. Efforts are now focused on moving a knife or powered clippers into the corn plant gaps with a pneumatic arm.

Fifth Update March 1, 2022
Weed control prototypes have been tested and final designs have been selected for the Thorvald. Stihl trimmer heads outfitted with solid blades will be used to cut weeds inter-row (the space between corn rows where tractors drive). A smaller modified trimmer head will be outfitted with a small saw blade to cut weeds intra-row (between individual corn plants. The intra-row trimmer will be mounted to an arm mechanism that can move it in and out of the intra-row space as the Thorvald drives down a row. The robot will not travel very fast, but it is hoped it will not have to stop either.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
A mechanism has been designed to move a small trimmer in and out between corn plants as the Weed Terminator moves down a row. The mechanism uses an elliptical motion to optimize the path of the moving trimmer between plants allowing as much time as possible to get the trimmer in and out without contacting any corn plants. Several parts needed for the design are of unusual shape. It was determined that it would be faster and less expensive in the long run to get a 3D printer to make these parts than to have them machined. The resulting parts will also be lighter and stiffer than an equivalent aluminum part if printed using a carbon fiber material. A 3D printer was purchased and is being used to make parts for the Weed Terminator.

Initially it seemed best to have a platform holding the weed elimination implements raise up and out of the way at the end of rows when the robot turns around. A mechanism accomplishing this has been designed, but due to the continually shrinking time for field testing, will not be constructed for initial testing. Instead, the weed cutting devices will continue to operate while the robot turns around cutting corn plants in the end rows. Yield losses will be minimal due to the tight turning radius of the Thorvald vehicle and end rows are considered somewhat sacrificial. If time permits, a tool raising mechanism will be attempted.

Seventh Update as of March 1, 2023:
An unexpected difficulty in developing methods to remove weeds between corn plants in each row (intra-row) is that the digital processing of camera images to locate corn plants takes too long to do in real time. This means the Weed Terminator would have to start and stop as it progresses through a field. It is desirable to keep the robot moving from both an energy use perspective and practical considerations. Therefore, the design

philosophy will now focus on removing weeds as close as possible to the corn plants without specifically trying to insert an implement between each plant.

Two central trimmer heads will be configured to remove most of the weeds between corn rows. Two additional, but smaller, trimmer heads will be configured to remove weeds between the central trimmers and the corn rows. These outer trimmers will be mounted with guards that prevent cutting of corn plants and they will be spring loaded so the guard rides along the corn plants. This mechanical solution should allow the Weed Terminator to remove almost all the weeds in a row without needing to know the exact position of each corn plant.

Eighth Update as of September 1, 2023:
Field testing of the Weed Terminator robot validated the weed control concept of using spring loaded cutters allowing weed elimination right up the corn plants. However, deviation in the straightness of corn rows exceeded the spring-loaded range of the cutters leading to cutting some corn plants. Some mechanical limitations of the cutterhead assembly were also discovered that made it difficult to reverse the direction of the robot once engaged in a row and some of the cutter motors were underpowered. Work this winter will focus on increasing the robustness of the cutterhead design and upgrading cutter motors with more powerful models.

Ninth Update as of March 1, 2024
Cutter head performance is being improved by replacing motors and motor controllers with commercial electric mower parts. Additional robustness is being explored by redesigning spring-loaded arms with an entire cutter head that can float side to side within a row. Moreover, the new design will not get stuck on corn plants if the robot needs to reverse its motion for some reason. Mechanical sensors to sense position in the row are also being considered to aid in-row navigation. Improved cutting performance will be demonstrated at Farmfest in August 2024.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
Controlling weeds in only one row instead of a dozen or more rows, as is the norm in production agriculture today, presents an opportunity for different solutions. Initial work developing weed control implements for an autonomous vehicle, the Weed Terminator, involved open ended brainstorming. Weeding was broken down into two regimes: inter row and intra row. Inter row is the space between rows of plants that is typically weeded with a cultivator implement that upends weed roots by turning the soil. Intra row is the space between individual plants in a row and is typically not addressed with mechanical weeding methods but is covered when spraying herbicide. After brainstorming many ways to control weeds in both regimes a matrix was developed ranking all the options based on qualities such as effectiveness, simplicity, energy demand, etc.

Top choices were prototyped to get a better feel for their actual performance with the best choices selected for implementation on the Weed Terminator. Several less common methods were tested like lasers and electrocution. The idea of spot spraying herbicide was also considered but rejected because it involves carrying a tank of heavy liquid that would need to be refilled. Already having to deal with recharging batteries, the team did not want another expendable commodity to manage. Also, the Weed Terminator would not be a potential solution for organic farmers if it used chemical weed control and organic farmers are likely to be the first farmers interested in a project like this because weeds are a bigger problem for organic farmers.

Because the project was focused on late term corn where weeds are generally larger than in early term corn and because preventing a weed from going to seed was considered successful, cutting weeds with a modified mower was selected as the most promising method from an effectiveness and energy use perspective. Cutting a weed in late term corn should end its reproductive cycle since the corn canopy will close shading the weed before it can regrow and produce seeds.

Two 10-to-12-inch mowing blades were fixed in a shroud to cut weeds in the inter row space. Initially, a mechanism was designed and prototyped to move in and out between corn plants perpendicular to a row to address weeds in the intra row spaces. However, the proposed camera and software system to identify corn plants in a row would not operate fast enough for an intra row mechanism without stopping the robot at each intra row gap. Stopping is undesirable so a new mechanism was developed to hold two smaller cutting blades (4") on spring-loaded arms with specially designed shrouds to allow the cutters to ride along the mature corn stalks bouncing in and out of the intra row gaps. This worked well but the spring-loaded arms did not provide enough range of motion to accommodate the inaccuracies inherent in the GPS navigation system. Moreover, the arms did not allow the robot to back up if needed and proved too fragile for the environment. The final design included just the inter row mowers which worked well.

ACTIVITY 3 Title: Robotic Vehicle Development

Description: In the initial phases of the development cycle, we will use a small research ground vehicle, like the Rover Robotics 4-wheel drive robot, to collect data and test individual components. However, such a vehicle will not have the ruggedness and payload capacity (and consequently battery life) to operate in real farm conditions. Specifically, a robotic vehicle platform is needed to carry the weed identification package and weed control mechanism through a field to eliminate weeds. The vehicle needs to be robust for an outdoor environment and able to travel effectively in loose soil with potentially muddy conditions. The vehicle will need to be as light as possible to maximize battery life and small enough to fit between standard crop rows that are planted 30 inches between rows. A SAGA Robotics Thorvald, or equivalent platform, will be procured and modified as needed to accommodate the selected weed control strategy(s) and navigation equipment.

ACTIVITY 3 ENRTF BUDGET: $315,756

Outcome	Completion Date
1. Develop initial vehicle requirements	10/1/2019
2. Purchase/modify Rover Robotics (or equiv.) research robot	2/1/2020
3. Adapt weed control prototypes to research robot	6/1/2020
4. Purchase/modify SAGA Robotics Thorvald (or equiv.) weed hunter robot	1/1/2021
5. Adapt selected weed ID/control systems to final weed hunter robot	5/1/2021
6. Performance testing of refined systems	9/1/2022

First Update March 1, 2020

A request for proposal (RFP) has been initiated through the University purchasing department. Desired vehicle characteristics have been specified and at least one potential supplier has been identified. The selection team has been set and it is expected that a suitable vehicle will be delivered by the end of this year.

Second Update September 1, 2020

An RFP was released for a final robotic platform for the weed hunter robot, but no bids were submitted. We are currently looking for an alternative vehicle. A few options have been identified, but a new RFP or exception to bid document will be needed to procure a vehicle.

Third Update March 1, 2021

A Norwegian company, SAGA Robotics, was found to provide a research robot called the Thorvald. This was the robot that provided the initial idea for this project. The robot has been purchased and will require the project team to design and build a chassis to configure the Thorvald to meet our needs. The wheelbase will span three crop rows leaving an empty center row for weed control implements. Robot delivery is not expected until at least October 2021.

Fourth Update September 1, 2021

Thorvald robot delivery is not expected until the end of the year. Final robot geometry is being worked out with a computer CAD model and on the pushcart mock-up that was built this spring. Moreover, the project is being used in a Mechanical Engineering senior design class. The design group will develop a design for the tool platform that will attach to the robot and allow mounting of cameras, sensors, control and power hardware, as well as the weed control mechanisms.

Fifth Update March 1, 2022
A frame made from carbon fiber tubes has been designed to mount to the Thorvald robot which will allow it to operate in a late term corn field. Moreover, the frame supports a central tower section resembling an airplane landing gear mechanism which will serve as a tool platform for weed control devices and allow the tools to be raised out of the way for turning around at the end of rows. All components for these structures have been ordered and will be assembled this spring.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
The SAGA robotics vehicle, Thorvald, ordered in December of 2020 finally arrived in late July 2022. The robot was uncrated and moved to a new space set up for assembly of the Weed Terminator robotic weeding platform built around the Thorvald base vehicle. The Thorvald shipment did not include the required battery charger. The robot can be operated with a wireless controller similar to an X-box controller, but it was locked inside a box on the robot along with the key needed to open the box. A crude key was fashioned to open the box and SAGA quickly shipped the missing battery charger. The Thorvald has been initialized and driven around a bit with the controller to establish its operating characteristics. The build quality is excellent, and the Thorvald seems to be a robust and efficient vehicle which should work well for our application.

A frame for the Thorvald has been designed using carbon fiber tubes to provide a rigid, but lightweight, structure to support weed control implements and maintain the desired geometry to operate in corn fields. Components for the frame have been ordered and delivered. Work this winter will focus on getting the frame, weeding implements, and miscellaneous structural and electronic components constructed and assembled on the Thorvald creating the Weed Terminator robot.

Seventh Update as of March 1, 2023:
A carbon fiber frame was fabricated to mate with the Thorvald wheel units and hold them at 60 inches apart to allow travel in a corn field. The frame was also sized to ensure the finished Weed Terminator would fit into the solar charging trailer for transport that was designed and built under a previous project. Several parts were designed and 3-D printed to facilitate connection of the frame to the Thorvald vehicle. The frame was designed to accommodate two large electrical boxes which will house navigation and controller hardware as well as batteries to power everything besides the wheel motors. The frame will also accept a tool strut that will attach to four centrally located points on the frame. The tool strut will allow rigid mounting of weed control implements, cameras, and other sensors.

The Thorvald has optional shock absorbers, but they were not installed on the delivered unit. Shock kits were ordered and installed. A few other spare parts were ordered including wire and conduit to lengthen an umbilical that stretches between the two sides of the Thorvald to pass power and communication signals to the wheel units.

Eighth Update as of September 1, 2023:

The Thorvald robotic vehicle has proved to be robust and reliable. The carbon frame had a weak point that was discovered while driving in rough terrain. The frame was reinforced with a metal strap and has performed well since. Additional batteries were desired to increase vehicle range and power all added electrical devices including cutter motors. The original battery shipped with the Thorvald is no longer available. SAGA Robotics recommended a replacement that they use in their current robot design. Four of these batteries were purchased to provide about 10 kWh of energy onboard. The total weight of the robot was found to be 840 lbs., which is near the maximum weight recommended by SAGA. The final geometry of the robot is a cube about 6 feet long on each edge. The remaining work will focus on improving the cutterhead robustness.

Ninth Update as of March 1, 2024
No changes are being considered for the robotic vehicle itself beyond the software and cutterhead improvements mentioned above.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
A Norwegian company, SAGA Robotics, was found to provide a research robot called the Thorvald. This was the robot that provided the initial idea for this project. The robot was ordered in December of 2020 and finally arrived in late July 2022 after many supplier delays and hold ups with customs. The Thorvald robot consists of two robot side units that each contain two wheel units, one in front of the other, and a control box between the wheels. The two side units are tied together with a flexible electrical conduit and two metal tubes clamped to both side units. The resulting assembly forms a four wheeled robot with four wheel drive and four wheel steering that can be configured to almost any width by changing the length of the metal tube connectors.

A frame for the Thorvald was designed and fabricated using carbon fiber tubes to provide a rigid, but lightweight, structure to support weed control implements and maintain the desired geometry to operate in corn fields. Thorvald wheels were placed 60 inches apart side to side so the robot would span three corn rows. The wheels ride in two outer rows leaving a central row for weeding. The frame was also sized to ensure the finished Weed Terminator would fit into the solar charging trailer for transport that was designed and built under a previous project. Several parts were designed and 3-D printed to facilitate connection of the frame to the Thorvald vehicle. The frame was designed to accommodate two large electrical boxes which contain navigation and controller hardware as well as batteries to power everything besides the wheel motors. The frame also includes a tool strut that attaches to four centrally located points on the frame. The tool strut allows rigid mounting of weed control implements, cameras, and other sensors. The total weight of the robot is 840 lbs., which is near the maximum weight recommended by SAGA. The final geometry of the robot is a cube about 6 feet long on each edge. The robot structure has proved to be durable with a few minor structural enhancements.

ACTIVITY 4 Title: Develop Autonomous Solar Charging System
Description: A solar charging station is being developed in phase 1 of this project and will be adapted to interface with the new weed hunting robot. Additionally, the charging station will be modified to allow the robot to dock and charge autonomously. This will require software for the robot to find the charging station and navigate to it when the robot's state of charge reaches a predetermined level. This will be performed in two phases: assuming that the location of the charging station is known in advance, a GPS + computer vision-based module will be implemented for the robot to get close to the station. Afterwards, a homing behavior will be developed for docking into the station. The interface geometry between the robot and charging station ports will be developed to maximize the ability of the robot to find and connect to the station while maintaining charger safety.

Software enabling the robot to return to the charging station autonomously will be tested on the small robot model at the University of Minnesota campus and later in fields at the WCROC and finally adapted to the more robust weed hunter robot.

ACTIVITY 4 ENRTF BUDGET: $76,446

Outcome	Completion Date
1. Develop initial sensor/control systems for finding charge station	5/1/2020
2. Design and fabricate robot/charger interface hardware	5/1/2020
3. Refine autonomous charging system with field trials	5/1/2021
4. Adapt final charging software and hardware to the weed hunting robot	5/1/2021

First Update March 1, 2020
Work on this activity has not yet started.

Second Update September 1, 2020
The solar charging trailer has been completed and commissioned including a level 2 automotive 6 kW charger. Adaptation to the weed hunter robot is dependent upon the, as yet unknown, final vehicle characteristics.

Third Update March 1, 2021
Further work on this task will have to wait until the Thorvald robot arrives late this year.

Fourth Update September 1, 2021
Further work on this task will have to wait until the Thorvald robot arrives late this year.

Fifth Update March 1, 2022
Further work on this task will have to wait until the Thorvald robot arrives late this year.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
Work has been completed to integrate lithium iron phosphate batteries into the charging trailer. Currently, the connection between the Thorvald vehicle and its battery charger is a complicated one. Significant modifications will be needed to automate the charging process. This will be investigated over the winter.

Seventh Update as of March 1, 2023:
Software is being developed to monitor the Weed Hunter's batteries. When the state of charge reaches some predetermined threshold the Weed Hunter will discontinue weeding and calculate a path back to the charging trailer so as not to drive over corn rows. Modifying Thorvald hardware to allow autonomous charging will be investigated but is probably beyond the scope of this grant due to battery communication signals being transmitted through the charging cable.

Eighth Update as of September 1, 2023:
The solar trailer has worked well for transporting the Weed Terminator and charging it when on location. No further changes are planned for the solar charging trailer.

Ninth Update as of March 1, 2024
A fault was discovered with one of the on-board batteries. It was removed and sent to the manufacturer for repairs. Autonomous charging was provided as a capstone project for a senior mechanical engineering class at the University of Minnesota (ME4054). A team of students was assigned to the project to develop a functional

specification, design, and prototype. The team designed a ramp to aid the robot in finding a spring-loaded charging receptacle. The charging receptacle counterpart was fixed to the robot. The team also used April Tags around the receptacle to provide location cues for the robot. April Tags are similar to QR codes but are simpler in design to be easily identifiable by cameras. Camera software can be readily written to steer a robot using April Tags as guide markers. The next phase of this project will use the student work to advance the goal of autonomous charging.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
This project leveraged a solar charging trailer that was developed under a previous autonomous weeding grant. The trailer consists of a 14-foot, vee nose cargo trailer with 3.3 kW of solar panels mounted on the roof. The panels are mounted to not exceed the roof perimeter and are on three levels. The bottom two levels contain three panels each and slide out on heavy-duty drawer slides – one to the left and one to the right. Inside the trailer everything needed for an off-grid solar energy system is mounted to the trailer walls. Equipment inside the trailer includes a solar/battery charge controller, a 6 kW power inverter, a level 2 EV charger, and an AC circuit panel with outlets. One enhancement that was made under this grant was to replace a lead-acid battery bank with two wall-mounted Lithium Iron Phosphate batteries. This significantly improved operation and handling of the charging trailer. The new batteries take up much less space and are significantly lighter than the ones they replaced. Wall mounting the batteries also allowed them to be placed over the trailer wheels improving trailer loading and handling characteristics. The lead-acid batteries had to be placed in the nose of the trailer because of their size and added almost 1000 pounds of weight to the trailer tongue.

It was desired to implement an autonomous charging scheme between the trailer and robot. This was not completed due to the complexity of the robot charging procedure and lack of time to develop software given the other software challenges described above. However, autonomous charging hardware was developed by a student team working on a senior capstone project for a mechanical engineering class. The Weed Terminator project team provided the design problem to the class and worked with them over the course of a semester to guide their efforts. In the end, they came up with a solution using April Tags as a visual guide system to guide the robot to a charging port. They also designed a prototype of adaptable charging plug/socket that could be used to make the electrical connection between robot and trailer. This will be pursued in future research.

IV. DISSEMINATION:

Description: Several different mechanisms will be utilized to disseminate the information. First, the weed hunter 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.

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENRTF Acknowledgement Guidelines.

First Update March 1, 2020
No dissemination efforts have been started.

Second Update September 1, 2020
No dissemination efforts have been started.

Third Update March 1, 2021
No dissemination efforts have been started.

Fourth Update September 1, 2021
No dissemination efforts have been started.

Fifth Update March 1, 2022
The weed terminator will be displayed at the Midwest Farm Energy Conference hosted by the WCROC in Morris on June 15th and 16th.

Update as of June 30, 2022:

Project extended to June 30, 2023 by LCCMR 6/30/22 as a result of M.L. 2022, Chp.94, Sec. 2, Subd. 19, legislative extension criteria being met.

Sixth Update as of September 1, 2022:
The Thorvald robot was not received in time to display at the Midwest Farm Energy Conference, but the Weed Terminator was included in a presentation about farm electrification at the conference.

Seventh Update as of March 1, 2023:
The Weed Terminator will be demonstrated at Farm Fest in August 2023. A seed plot has been reserved and corn will planted this spring to facilitate the demonstration.

Eighth Update as of September 1, 2023:
A seed plot and tent were rented for display at Farmfest in Redwood Falls, MN, during the show from August 1 through 3. The Weed Terminator was run in a live weeding demo in the corn plot three times a day. It was on display in front of the tent in between demos. The whole show was very successful – there was a lot of traffic through the tent and for the scheduled demos.

Ninth Update as of March 1, 2024
The Weed Terminator will be featured in a presentation and tour at the WCROC Midwest farm Energy Conference on June 26th and 27th in Morris, MN. The Weed Terminator will also be demonstrated at Farmfest again in August 2024.

Final Report as of June 30, 2024 (to be submitted before August 15, 2024):
The Weed Terminator robot was actively demonstrated several times each day in a corn plot at Farmfest. Farmfest is a large state-wide farm show which was held from August 1-3, 2023. The Weed Terminator was also included in presentation material and actively demonstrated at the Midwest Farm Energy Conference held in Morris, MN, June 26th and 27th, 2024. The Weed Terminator was also featured in a segment of "The Prairie Sportsman", a production Pioneer Public Television. The segment aired on April 28, 2024.

V. ADDITIONAL BUDGET INFORMATION:

A. Personnel and Capital Expenditures

Explanation of Capital Expenditures Greater Than $5,000:
One small research robot, like the Rover Robotics 4-wheel drive robot, $10,380. This robot will be used to test concepts and collect navigation data; however, such a vehicle will not have the ruggedness and payload capacity (and consequently battery life) to operate in real farm conditions. The robot will continue to be used for field data collection after this project is completed.

One robust robotic platform, like the SAGA Robotics Thorvald, $130,000. This platform will be used to carry selected weed control strategy(s) and navigation equipment, becoming a weed hunter robot capable of farm fieldwork. The robot will continue to be used for fieldwork research after this project is completed.

Capital expenditures over $5,000 paid for with the appropriation will continue to be used for the same program through its useful life, or, if the use changes, the Environment and Natural Resources Trust Fund will be paid back an amount equal to either the cash value received, or a residual value approved by the LCCMR director if it is sold.

Explanation of Use of Classified Staff: N/A
Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours for entire duration of project: 15,350	Divide total personnel hours by 2,080 hours in 1 yr = TOTAL FTE: 7.4

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

Enter Total Estimated Contract Personnel Hours for entire duration of project: 325	Divide total contract hours by 2,080 hours in 1 yr = TOTAL FTE: .2

VI. PROJECT PARTNERS:

A. Partners outside of project manager's organization receiving ENRTF funding

B. Partners outside of project manager's organization NOT receiving ENRTF funding

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

Successful development of economic solar-powered robotic systems for weed control in 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 in phase 1 of this project and will provide invaluable experience in developing products for the commercial market.

VIII. REPORTING REQUIREMENTS:

- Project status update reports will be submitted March 1 and September 1 each year of the project
- A final report and associated products will be submitted between August 30 and October 15, 2024

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. Budget Spreadsheet
B. Visual Component or Map
C. Parcel List Spreadsheet
D. Acquisition, Easements, and Restoration Requirements
E. Research Addendum

IX.

B. VISUAL COMPONENT or MAP(S):

The Rover Robotics 4 wheel drive robot is a readily available robot testing platform from a Minnesota company. It can be configured to carry a variety of payloads and is electric powered. The project team has experience with this platform and will use it, or something similar, to test navigation systems and weed

The Weed Terminator robot demonstrating autonomous weeding in a corn plot at Farmfest in August, 2023.

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2019 Budget Spreadsheet
Legal Citation: M.L. 2019, First Special Session, Art. 4, Chp. 2, Sec. 2, Subd. 08g
Project Manager: Eric Buchanan
Project Title: Agricultural Weed Control Using Autonomous Mowers
Organization: Regents of the University of Minnesota
Project Budget: $900,000
Project Length and Completion Date: 5 years, 6/30/2024
Today's Date: 1/9/2025

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Budget [1/9/2025]	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits)	$ 696,862	$ 696,862	$ -
Project coordinator - Eric Buchanan - $55,220 (77% salary, 23% fringe)FTE yrs 1-2, 10%, yr 3, 50%			
Prject Engineer - WCROC - $179,852(77% salary, 23% fringe)FTE yrs 1, 50%, yr 2-3, 100%			
Farm technician - WCROC - $50,000 (77% salary, 23% fringe)FTE yrs 1-2, 25%, yr 3, 0%			
Research technician -BBE - $50,000 (74% salary, 26% fringe)FTE yrs 1-2, 28%, yr 3, 0%			
Computer Scientist - Junaed Sattar - $49,969 (74% salary, 26% fringe)FTE yrs 1-2, 8%, yr 3, 6%			
Grad student RA#1 w/ Dr. Volkan Isler - CSE - $151,439 (86% salary, 14% fringe)FTE yrs 1- 3, 50%			
Grad student RA#2 w/ Dr. Volkan Isler - CSE - $151,439 (86% salary, 14% fringe)FTE yrs 1- 3, 50%			
Professional/Technical/Service Contracts	$ 7,000	$ 6,950	$ 50
Contracts for robot platform modifications and/or weed control equipment design from TORO or equivalent following U of MN policies, $15,000			
Equipment/Tools/Supplies	$ 57,042	$ 57,042	$ -
Rover Robotics charging dock, or equiv., $1,450			
Rover Robotics payload supplies including a laptop computer with NVidia GPU, GPS systems, multiple cameras, component enclosures, and supplies for wiring, soldering, etc., $14,969			
Weed hunter robot sensors & control electronics for Dr. Isler, $15,000			
Weed control apparatus supplies and equipment for prototyping and fabrication, $15,000			
Solar charging trailor modifications to accommodate autonomous charging, $4,500			
Capital Expenditures Over $5,000			
Weed hunter robot platform vehicle (SAGA Robotics, Thorvald, or equiv.) following U of MN policies, $130,000	$ 94,947	$ 94,947	$ -
Rover Robotics 4 wheel drive robot platform with charger, payload package; or equiv. following U of MN policies, $ 13,380	$ 9,955	$ 9,955	$ -
Printing	$ 184	$ 184	$ -
Printing conference materials for Midwest Farm Energy Conference to be held at the WCROC in 2021, $1,500			
Travel expenses in Minnesota	$ 12,646	$ 12,554	$ 92
Twelve trips by CSE and BBE Faculty from Saint Paul to Morris, MN (340 miles @ $.58 / mi) , $2,366; Lodging and meals for CSE and BBE Faculty in Morris (3 people / 6 nights @ $120 / room and $40 ea for meals), $ 2,880			
WCROC Staff travel from Morris to Twin Cities (340 miles and 4 trips @ .58), $789; A Lodging and meals for WCROC staff in St. Paul (2 people / 4 nights @ $120 / room and $40 ea for meals), $ 1,280			
Conference-Farmfest Exhibitor Fee, Tickets, Signage, and Display, $2,500 for public presentation of the project and dissemination of project information; Travel for one in-state outreach event FarmFest (4 people, 4 days /3 nights, 2 trips, 400 mi @$.58/mi), $464 Lodging and meals for one in-state outreach event FarmFest (4 people, 4 days /3 nights, $120 / room, and $40 ea for meals), $1,920			
Other	$ 21,364	$ 21,364	$ -
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. $16,681			
Computer Aided Design software license, 2 seats at $2,400 each			
COLUMN TOTAL	$ 900,000	$ 899,858	$ 142

check

OTHER FUNDS CONTRIBUTED TO THE PROJECT	Status (secured or pending)	Budget	Spent	Balance
Non-State:		$ -	$ -	$ -
State:		$ -	$ -	$ -
In kind:		$ -	$ -	$ -

PAST AND CURRENT ENRTF APPROPRIATIONS	Amount legally obligated but	Budget	Spent	Balance
Current appropriation:				
Past appropriations: ML2018 CH 214 ART 4 SEC2 SUB 08D E818WCM		$ 750,000	$ 699,793	$ 50,207