Autonomous Robotic Lawnmower Implemented with Computer Vision Functionality

ECE 4012 Spring 2018 Senior Design Project

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Executive Summary

This project details the design, fabrication, and field testing of a convolutional neural network intended to operate the next generation of autonomous robotic lawnmowers. Currently available autonomous lawnmowers on the market move in undefined paths within set barriers, and are programmed to mow a lawn indefinitely until they are called back to a base station. By implementing a computer vision approach via a graphics processing unit (GPU) based neural network, our proposed autonomous lawnmower will be able to intelligently determine the difference between mowed and unmowed grass, mow the grass in a defined path that it determines to be the most efficient, and continue to learn and improve its algorithm over the course of its lifetime. The result is an artificial intelligence that will produce a smarter, more efficient, and overall superior autonomous lawnmower.

The project does not encompass any obstacle detection or actuation. Instead, the work is centered around the algorithm designed to recognize the state of grass. The physical implementation includes a folding cart that mimics a lawnmower chassis housing one or two high-end cameras along with the neural network ‘black box’. Neural net implementation is done on TF Learn with Python, building on the many templates exist on the Internet today. The project budget was almost exclusively expended on the cameras and GPU, which leads to an estimated cost ceiling of $1000 for the MowMow lawnmower.

1. Introduction

The autonomous lawnmower will run on an algorithm designed to accurately distinguish between cut and uncut grass, which will be based in an artificial neural network housed on a GPU. The neural network will be trained on the superior processing power of the GPU, and will be uploaded onto a smaller processing suite connected to the cameras for testing and debugging. Our team is requesting $1000.00 in total to finance the GPU, cameras, and the processor that will comprise our prototype of the autonomous lawnmower.

1.1 Objective

The objective of MowMow is to design a computer vision system that will distinguish between unmowed grass and grass that has been mowed by a lawnmower. The computer vision component will be composed of a neural network that receives inputs from digital cameras on the front and back of the mower to learn what is unmowed grass and what is mowed grass, allowing it to function for a variety of grass species. MowMow's design will ultimately be used in an autonomous lawnmower manufactured by Stanley Black & Decker. The grass recognition system will ultimately allow the lawnmower to navigate around a yard without using positional data. If the lawnmower encounters a section of grass it has already mowed, it will correct its heading to continue along an area it has not yet passed over. Since patterns are important to upkeep of lawns, avoiding the problem of repeatedly mowing cut grass would give MowMow an advantage over its competition . In addition, this would also decrease energy consumption, thereby boosting longevity.

1.2 Motivation

Current autonomous lawnmower designs involve boundary and position-based navigation. A physical wire boundary is installed around the perimeter of the customer's yard [1]. If the lawnmower crosses this perimeter wire, it will reverse and redirect itself. The wire perimeter adds additional steps in the installation process and can be prone to damage [2]. When navigating a yard, the autonomous lawnmower often crosses over areas it has already covered as a result of inefficient pathing. MowMow plans to eliminate both the perimeter wire and the potential for path retracing using the combination of sensor fusion and a neural network. The MowMow design will be able to recognize cut grass versus uncut grass, preventing the lawnmower from retracing its own path. This recognition system will also eliminate the need for a perimeter wire, as it will be able to differentiate between grass and other surfaces. By providing an easier installation process in addition to higher time and power efficiency, MowMow would be smarter and more eco-friendly than its competition.

The recognition system itself could prove useful in a variety of similar applications. Due to the self-learning nature of the neural network, the design can adapt to different species of grasses. Additionally, the boundless navigation component can adapt to any size area of yard. Ultimately, MowMow's sensing and actuating model will put Stanley Black & Decker's autonomous lawnmower systems ahead of its industry competitors.

1.3 Background

Currently, a variety of fully functioning autonomous lawnmowers already exist on the market, and most are produced by small-scale manufacturers and sold either on Amazon.com or from their own company websites. Some larger companies, like Honda, also have autonomous lawnmower models for sale, and may be sold through home improvement stores such as Lowe's. As these companies developed these robots individually with the express purpose of a market release, no research on their development process is available to the public as customary in proprietary non-disclosure agreements.

All currently available autonomous lawnmowers operate similarly to the popular Roomba robotic vacuum cleaner from iRobot, and begin their mowing protocols starting at a base station and moving around the boundaries of the lawn randomly until all area has been covered. No grass recognition system is present in these implementations, and lawn boundary detection is done primarily in two different ways: one implementation uses infrared or ultrasonic sensors on the lawnmower's chassis that will stop and pivot the robot whenever it gets too close to an obstruction or other terrain that is not grass; the other implementation involves installing a low voltage wire fence system around your lawn, which communicates with the lawnmower's own sensors to prevent it from entering these areas [3]. Both implementations are simple and inexpensive to install, but neither are intelligent or particularly efficient.

Artificial neural networks on GPUs are not new inventions, and various code examples written in a variety of languages are available online for public use. The convolutional neural network (CNN) used in MowMow is implemented for complex image recognition, in which processing layers are used to generate a network topology that can be manipulated in a number of ways. The convolution layer serves as the mesh between an input image and a set of learnable filters [4]. These layers are then applied to the GPU with an open-source framework.

2. Project Description and Goals

The goal of MowMow is to create a self-learning system that will guide Stanley Black & Decker's autonomous lawnmower around a yard without using traditional boundary-based designs. The system will include camera feedback to gather information from the environment and a neural network to process the information from the environment. Each subsystem will include the following:

- Sensors
    - Front camera to record images of the grass - GoPro HERO5 Black 4K Ultra HD
- Neural Network
    - Robot-mounted processing unit designed to link neural net to camera feed - Raspberry Pi single board computer
    - Graphics processor unit (GPU) which will house and train the network - Nvidia GTX 1080

3. Technical Specifications

MowMow should have at least 70% accuracy with its cut or uncut grass detection algorithm. Table 1 contains operational and performance specifications for the camera provided by our sponsor, GoPro HERO5 Black 4K Ultra HD. It provides advanced video stabilization, multiple recording/capture modes, touch screen, and performs well in all lighting conditions. A major advantage is the presence of a Github Python library, thereby allowing wireless control[5].

Recording Modes	4K/30fps,1080p/120fps
Capture Modes	12MP raw image
Battery Life	60-90 mins (4K)
Connectivity	Bluetooth, Wi-Fi, Github lib.
Estimated Cost	$200-$299

Table 1. Technical specifications for the camera mounted.

A GPU with satisfactory processing power is necessary to perform image processing on hundreds of images and house an ever-changing neural network. Table 2 contains the basic specifications of the Nvidia GTX 1080 (8GB version), which was provided by our sponsor.

Memory	8 GB GDDR5X
Memory Speed	10 Gbps
Architecture	Pascal
CUDA Processing Cores	2560 @ 1733 MHz
Estimated Cost	$550 - $700

Table 2. Technical specifications for the Nvidia GTX 1080.

4. Design Approach and Details

4.1 Design Approach

There are two distinct components to MowMow: the sensing and the neural network. The sensing will be responsible in providing inputs to the neural network to process. The neural network will process the feedback from the camera sensor and detect whether the patch of lawn is mowed or not.

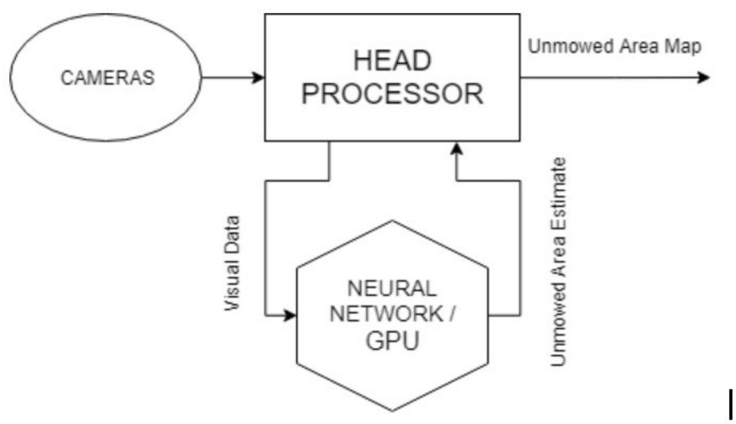

Figure 1. Tentative System Flowchart of the design in question.

4.1.1 Sensing

The sensing is comprised of the same camera used to capture grass images for training on the neural network. A compact box containing a raspberry pi that runs a state machine to achieve the final demo is also mounted, while being connected to Computer A. The image captured is wireless transferred to Computer B with the neural network weights.

The network applies its prediction, sending it back to Computer A, which then detect the status of the patch of grass and sends a command to the lawnmower. The front camera will be in charge of providing images of the upcoming patch of grass. A back camera could be used to make sure that the grass is mowed. Regardless of the orientation, the cameras will be exposed to vibrations and wobble due to non-flat topologies and the motor and may capture blurry images as a result.

4.1.2 Neural Network

In order to determine the difference between mowed and unmowed grass, complex image processing is required and a variety of neural network strategies are viable for this task. Our team has decided to use a convolutional neural network (CNN or ConvNet) to process images, which employs filters that break an input image down into its defining identifiable objects through multiple rounds of convolution, and then identifies these objects with labels when the image is pieced back together. Because the neural network will need to process hundreds of images to learn, it will require the processing power of an Nvidia GPU. For a simpler and more efficient development process, the network will be written using the Tensorflow library that interfaces with Nvidia CUDA. Once written and trained, the neural network will be uploaded onto a central processor and connected to the cameras to receive video feed, allowing it to operate in the field.

The prototype network developed in this project has 12 layers in total. The input array is fed into the first convolutional layer (referred to as CONV), followed by one pooling layer (referred to as POOL), followed by two more CONV layers and a POOL layer, then funneled down to 4 labels (3 for demonstration) in 4 fully connected layers with 3 dropout layers in between them. The dropout layers are active only during training, and are bypassed at prediction mode.

4.2 Codes and Standards

Autonomous lawnmowers and their lawnmowing algorithms are not held to any currently existing standard. While there are many more complex applications of artificial neural networks, as well as those implemented on FPGAs as opposed to GPUs, we will not go beyond what is stated in this proposal and therefore do not run the risk of deviating from any standards present within the coding community at large.

IEEE 802.11, and by extension 802.11b, is the standard that will be used for wireless Internet access since our team decided to use it in the programming portion of the project.

4.3 Constraints, Alternatives, and Tradeoffs

One design alternative discussed was having the mower attached to a fixed pole in the middle of the yard and mow grass by moving in circles of increasing radius with the fixed pole as the center. This approach prevents the mower from repeatedly cutting already mowed grass but is not visually appealing and hence, not marketable. The final design should work for majority of American homes and thus should account for different yard shapes, weather conditions and grass species.

In determining a GPU for the neural network, the obvious constraint is cost, which goes up as you browse through more powerful graphics cards. The general consensus within the community is that the GTX 1060 (6GB) (previously proposed) is a good GPU to get if you’re entering the world of computer vision and machine learning and that the GTX 1080ti/GTX Titan XP are the premier graphics cards for more complex machine learning applications. Because the latter two cards are priced at upwards of $1000, the 1060 is the more attractive option. Another option was purchasing an Nvidia Tegra GPU, which is a combined CPU-GPU-memory controller System on Chip (SoC) processor that would make the implementation of the network easier, though at the cost of processing power.

Other discussed sensing applications included multispectral imaging and thermal imaging. Multispectral imaging cameras would provide much more visual information and detail regarding recorded grass. However, these systems were too outside of the budget for this project. Thermal imaging would give the neural network information on temperature, as it changes with grass depth and density. However, the temperature gradient for the grass is not large or significant enough to be useful. Also, different levels of sunlight and shading would affect the thermal readings. In the end, thermal imaging proved to be too inconsistent to implement.

5. Final Project Presentation

Our Capstone Design Expo demo and presentation consisted of:

- A short 3-minute video summarizing the journey of the project and the strategy behind data acquisition, labeling, and the neural network

  A live demonstration of our neural network's classification algorithm, running on a Raspberry PiZero connected to a GoPro Hero 5 and auxiliary laptop running a fully trained version of the CNN
- Two live grass beds, intended to represent an unmowed lawn and a mowed lawn, as the subjects of the live demonstration

- A monitor displaying the results of the neural network after the demonstration, with the original GoPro image taken underneath a semi-transparent overlay with multiple colors representing if a frame in the image is irrelevant, unmowed grass, or mowed grass.

The live demonstration was run by pressing a push button connected to the Raspberry Pi in a box. This button sent a signal to the wirelessly connected GoPro, which took a picture of the grass bed and transferred the image back to the Raspberry Pi. Once received, the image was sent to the laptop and analyzed using Kristian and Eren's modified CNN, which analyzed the image, ran it through filters, and returned the image with an overlay. This overlay was presented on the monitor for 10 seconds as a proof-of-concept for our CNN.

Our design project poster also presented a significant amount of data pertaining to the project, including initial results from Tensorflow's data analytics as well as more in-depth explanations of the labeling GUI, CNN overlay, and comprehensive results.

6. Guidelines to Recreate Critical Project Components

6.1 Grass Beds

Two live grass beds were grown in order have a live demonstration at the final presentation. After testing a small sample in a plastic container, the type of grass selected was wheatgrass. Wheatgrass was chosen because the species grows indoors with low lighting and takes around two weeks for the grass to germinate and to grow to full height. One grass bed was intended to hold unmowed grass while the second was intended to hold mowed grass.

Ultimately, the mowed grass bed was cut to an arbitrary height with scissors and the neural network was unable to distinguish between the two beds. This could be helped by researching an alternative method of trimming the grass so that it mimics grass cut by a lawnmower. The supplies used and steps followed to grow the grass are as follows:

6.1.1 Supplies

- Wheatgrass seeds (2 lb.) [12]
- Potting soil (50 qt.) [13]
- 2 Under-bed plastic storage containers (60 qt) [14]

6.1.2 Growing Procedure

1. Once the seeds have been acquired, pour one pound of seeds into a container large enough so that they fill at most one third of it, as they will expand over the next couple of days.
2. Rinse the seeds and fill the container with water and allow the seeds to soak for ten hours or overnight.
3. After the first ten hours, change out the water in the container and allow the seeds to soak for another ten hours. Repeat this process for a total of three ten-hour soaks.
4. After the three soaks, the seeds should have germinated and exhibit small, white roots.
5. For one pound of seeds, fill one plastic container with one 25-quart bag of potting soil.
6. Spread the seeds in an even layer over the soil. Do not cover the seeds with the soil.

7. Once the seeds have been spread onto the soil, cover them with damp newspaper. This will keep the seeds moist as they start to sprout. If the newspaper starts to dry out, spray it with water to re-dampen it.
8. After 2-3 days, the seeds should root into the soil and begin to sprout. At this point, the newspaper can be removed.
9. Once sprouted, the grass should be watered daily and kept in moderate sunlight. It will grow to its maximum height of around 6-8 inches over the course of 7-10 days. Animals, specifically cats, are very attracted to this species of grass, so it is advised to keep the grass away from pets.

6.2 Data Capturing, Labeling, and Analytics

1. With the GoPro, record a small length 720p or 1080p (60fps) video of a lawn, keeping the camera at a height that mimics the perspective of a camera on a lawnmower.

2. GT facilities were very open to sharing their lawn-mowing schedules for the semester. Videos of the lawns including, but not limited to Flagpole lawn and Tech Tower lawn, were collected right before and right after they were mowed.

3. Using OpenCV or ffmpeg, extract images every 60 frames or one second. This quantity can be changed to make sure there lie subtle variations in each image, otherwise the data will have redundancies.

4. We created a labeling GUI in order to categorize each frame as one of four categories: Mowed, Unmowed, Unknown, or Irrelevant.

a. Mowed and Unmowed are self-explanatory.

b. Unknown means the frame contains some grass and some Irrelevant parts (typically at the horizon)

c. Irrelevant means it is not grass (like part of the sky, trees, or a building).

5. In the custom GUI, images were then each divided into 100 frames (split into a 10x10 grid) to be labeled. A primary data set containing about 2000 individual images was procured.

6. This made the process of labeling the data more intuitive, but never the less time intensive. Batch labeling was used to marginally sped up by adding the functionality of labeling row by row, and labeling the top and bottom 3 rows default as 'Irrelevant' and 'Mowed' or 'Unmowed' depending on the video

7. To add more on the process of batch labeling, the csv file containing the labeled information from the GUI will was processed in MATLAB to generate heatmaps which gave positional statistics of each labeling category on the 10x10 grid map. Smart techniques can be used to speed up the labeling process. However, it is vital that the perspective should be similar to that of a camera on a lawnmower.

8. Once each frame was labeled, the labeling data was fed into a TensorFlow convolutional neural network and processed on a GTX1080 over the course of anywhere from 2-3 days.

6.3 Pre Processing and Attribute classification

1. To make the CNN more robust, input images were distorted, flipped and rotated to add more data points to the ones already existing.
2. Another approach we tried was to extract numerical attributes from an image and train a neural network on just those. Attributes extracted were clearness, brightness, average red value, average green value, average blue value, number of edges, and average edge length
3. We expected grass to have higher green values than irrelevant images. Assuming the image was clear, unmowed grass was expected to have fewer edges that are on average longer, and vice versa for mowed grass.
4. For the attributes extracted, these were fed along with their corresponding labels into a Neural Network run on Python's sci-kit learn library.

6.4 Project Links with description

1. Description of the project structure and scripts including the demo, GUI, neural network: https://kakaday22.github.io/MowMowInc/
2. Github: https://github.com/kakaday22/MowMowInc
   https://github.com/KonradIT/gopro-py-api
3. Capstone Poster (PPT format): https://drive.google.com/file/d/19-lcOfOGCsusepNdjEOrqj7_dsrtGhYr/view?usp=sharing

7. Conclusion and Future Considerations

The neural net with attributes led to a success rate of 76% on the validation set. This included all the irrelevant images, which skewed the results however. The Convolutional Neural Net led to a success rate of 80% on the grass beds grown, and 90% on the 1865 images of lawns. The neural net was close to 100% when it came to identifying the irrelevants but the rate was lower considering just mowed and unmowed images (70%)

Issues were encountered due to the camera battery draining fast at the high resolution modes. Also, lighting conditions of training could were not synonymous with the lighting conditions in Capstone which led to the neural network mispredicting frames it would usually get right. To conclude, although the CNN displays proficiency in distinguishing multiple objects, it is tough to see it as more than a layer of logic, to help increase prediction confidence or perhaps be invoked under certain conditions.

Future work will revolve around increasing the size of the image set, supplying it with different grass species and lighting conditions in order to observe a point of convergence. In addition, research into a compact, embedded data capturing tool began. This is being developed with the intention of attaching it to a drone or movable cart, to easily store/transmit relevant data. More development into such a tool could automate the data collection to certain extent. A mechanical stabilizer can be also be part of this, making this a strong tool for moving devices that need to recognize objects and take action.

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