Here is presented a report for Schiller Grounds Care, cataloging the design and validation processes.
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Executive Summary

Schiller Grounds Care, Inc. is a leading manufacturer of gardening and grounds care equipment. One of Schiller’s best-selling pieces of equipment is the Mantis miniature tiller and cultivator. Schiller has asked the University of Delaware design team to redesign the transmission of the Mantis tiller to incorporate a reversing feature.

In order to make the Mantis more versatile as an all-purpose machine, Schiller desires the option of having the output shaft rotate in the opposite direction from the perspective of the user. In doing so, the Mantis will be more effective for attachments such as a sweeping arm or snow thrower. Currently, the Mantis uses a worm and worm gear system driven by a combustion engine or electric motor that has been optimized for tilling torque and speed. Because the device is primarily used for tilling, Schiller wishes to incorporate this reverse feature into the current machine without changing the normal tilling output or drastically increasing the size of the transmission housing. The main purpose of this project is to design such a feature, focusing solely on the gearing involved and the method for actuating the reversing mechanism.

Through communication with Schiller, the design team compiled a list of designable and measurable metrics of success and target design values. A design concept to best achieve these success metrics was envisioned and fabricated into a prototype. The functionality and success of the prototype was then tested. From these results, the design team worked with Schiller to decide the best path forward for further testing and eventual incorporation of the reversing design into the commercial product.
Introduction and Project Scope

Schiller Grounds Care, Inc. was established in early 2009 with the merger of Schiller-Pfeiffer, Inc. and Commercial Grounds Care, Inc. Schiller Grounds Care, Inc. manufactures gardening, landscaping, and grounds care equipment brand names such as Little Wonder®, Classen®, Bob-Cat®, and Mantis®. The Mantis brand has been on the market for over twenty-five years and boasts the Mantis tiller/cultivator, the world’s best-selling tiller with over one million customers. Although the Mantis tiller already has attachments for tasks such as edging, dethatching, and aerating, Schiller wishes to expand their market and sell additional attachments for processes like sweeping and snow-throwing. In order to make effective attachments for such tasks, the output shaft of the Mantis tiller should rotate in the reverse direction from the proper tilling direction, so that the debris is thrown away from the user instead of towards. In order to more effectively design a reversing feature, the design was divided into three subsystems: the gearing subsystem including the necessary gears for reversing the output shaft, the actuation subsystem including the way in which the reverse feature is engaged in the transmission housing, and the control subsystem including the interface through which the user will manage the reversing feature. Schiller has asked the design team to focus solely on the gearing and actuation subsystems for this project.

Design Requirements

Wants and Constraints

The design team spoke with representatives from Schiller in order to better define their wants for the design. One important consideration specified was for the transmission to occupy a footprint very similar to the current design. The size and shape of the transmission affect both the placement of the tilling blades and attachments and where the engine must be placed on the tiller. Specifically, the design team must concern itself with the width of the transmission housing for our new design. As the tiller is dragged through the ground, the transmission creates a resistance through the soil. A larger transmission housing will increase this resistance, making it harder to use the tiller for its primary function.

Schiller also requested the team to consider the center of gravity of the tiller. One of the biggest reasons for the success of the Mantis is its low center of gravity. If the center of gravity of the machine falls outside the width of the tines while tilling, the blades will not dig into the soil, making the machine less useful as a tiller. It is important for the functioning of the machine to keep the relatively same center of gravity and not raise it too much.

The Mantis tiller is designed and engineered for optimal tilling success. The output torque, speed, and power of the machine are carefully managed through the engine and gear ratios in order to till efficiently. Schiller expressed that they would not like to change or reduce the output in the forward direction in order to maintain these optimizations.

Next, Schiller expressed a desire for the new transmission to have a similar cost of parts and assembly to the old transmission, so the reversing mechanism can be included in the tiller without
having to increase, or at least not drastically increase, the cost in order to preserve the current profit margin.

Another want for the new transmission is for it to have a simple actuation; the process of switching the tiller from forward to reverse, and vice versa, should be clear and should not involve more than a couple of easy-to-remember steps. This way, it will appeal to gardeners who are not especially mechanically inclined. In addition to a simple interface, the transmission should be easy to manually engage in both forward and reverse. If the entire target demographic of the tiller is not strong enough to switch the tiller between gears, Schiller may lose current or potential customers. As a safety concern with the actuation, Schiller expressed a desire for the engine to be shut off and the tines removed during shifting. This is necessary to avoid accidental injury to the user. Because of this safety constraint, the team was able to disregard concepts concerning shifting a running system.

The company wants the new transmission to be element-resistant and durable. Because the tiller is usually operated to churn up the ground, soil, plants, water, etc., debris will be coming into contact with the housing of the transmission. In order to ensure reliable operation, the housing must be able to withstand such contact. The company’s reputation depends on how well its products hold together over their expected lifespan, and therefore something as critical as the tiller’s transmission must be capable of properly operating for as long as possible. This will help maintain the reputation of the Schiller name and their ability to sell the tiller and other products.

Mechanically, the possible design concepts are constrained by the power output from the motor. Schiller provides three distinct motors for the Mantis: a two-stroke, a four-stroke, and an electric. The finalized design must be compatible with these motors, particularly the current four-stroke engine. In addition, the tines on the tiller have a set output torque for a given engine RPM that should be matched by the design.

Table 1: Table of wants, as discussed by communication with Schiller

<table>
<thead>
<tr>
<th>Wants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively Same Footprint</td>
</tr>
<tr>
<td>Relatively Same Center of Gravity</td>
</tr>
<tr>
<td>Relatively Same Tilling Output</td>
</tr>
<tr>
<td>Low Cost</td>
</tr>
<tr>
<td>Simple Design</td>
</tr>
<tr>
<td>Easy to engage</td>
</tr>
<tr>
<td>Durability/Element Resistant</td>
</tr>
</tbody>
</table>
Metrics and Target Values

The width of the gear housing in the transmission is a metric that the design team aims to meet. The width of the current transmission housing at its widest point is 2.375in. The design team is designing for no more than an additional 0.375in to each side of the transmission, giving a total maximum width of 3.125in. While tilling, the gear housing is fully under the surface of the ground being tilled. Any drastic increase in the width of the gear housing will increase resistance through the soil being tilled, making the job require more physical labor. Additionally, in an ideal design, the gear housing with the reversing transmission will be identical to the current design, eliminating the need to alter the assembly or manufacturing process of the current transmission housing.

The center of gravity of the tiller is a very important aspect. If the center of gravity rests too high on the machine, the tines will not dig into the soil appropriately, severely decreasing the effectiveness of the machine. As a result, the team is designing to maintain as close to the current center of gravity as possible. The design should not raise the current center of gravity by more than 0.5in.

The current four-stroke tiller outputs a maximum 31ft-lbs of torque at the tines, and a maximum rotational velocity of about 240 RPM. These current values are kept as target values for the torque and RPM metrics for the forward direction of the reversing feature. As mentioned above, it is important for Schiller to maintain the normal, forward output of the device.

The low cost of the Mantis is made possible by the low cost of manufacturing and assembly of the device. The current cost of parts and labor for one tiller is $40.83. In order to maintain the low price of the Mantis, the target value for total cost of parts is chosen as $60. Additionally, the design team is designing for an assembly cost of less than $25. By designing a reversing transmission for under this target total cost, the retail price of the Mantis will not have to increase by very much, making the tiller still accessible to the current target customers.

Factored into the cost of parts and cost of assembly is the added number of parts of the transmission. More parts leads to longer assembly times, ultimately leading to higher assembly costs. More parts also directly affect the total cost of parts. To cross-correlate the wants and reach a desirable design, the team is targeting to add no more than ten total parts to the current transmission.

The Mantis is designed as an easily-portable miniature tiller, able to be used and carried by owners of average size and weight. The lightweight design is an important selling point and makes the tiller widely accessible. It is important for the added reversing mechanism to not add any substantial weight to the current design. Schiller and the design team have chosen to not add more than 5lb to the current design, in order to maintain the portability of the tiller.
Table 2: Table of metrics and target values, as discussed by communication with Schiller

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing dimensions</td>
<td>raised ≤ 0.75in wide</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>raised ≤ 0.5in</td>
</tr>
<tr>
<td>Output (power, torque, rpm)</td>
<td>31ft∙lb, 240RPM</td>
</tr>
<tr>
<td>Cost of parts</td>
<td>raised ≤ $34 ($60 total)</td>
</tr>
<tr>
<td>Cost of assembly</td>
<td>raised ≤ $10.50 ($25 total)</td>
</tr>
<tr>
<td>Number of parts</td>
<td>raised ≤ 10</td>
</tr>
<tr>
<td>Weight</td>
<td>raised ≤ 5lb</td>
</tr>
</tbody>
</table>

**Benchmarking**

In order to begin the step of concept generation, the team performed some benchmarking to discuss some early possible solutions to the problem. Competitive models, such as the miniature tillers manufactured by Honda, Craftsman, and Yard Machines have been investigated for comparison. None of the competing models exhibited possible working solutions to this unique problem. The only tillers found with reversing features are large, rear-tine tillers, and their solutions are not applicable to this problem. Additionally, the team investigated certain “combo tools”, like those of Echo Power Equipment, capable of different attachments with different features including tiller/cultivators. None seemed to provide a feasible solution to the problem, however, as all the directional features were included in the attachments only, if ever.

The team also investigated current technology before attacking the design process. They became familiar with the current Mantis transmission and assembly process. Additionally, they researched previous work in the field. A previous design team has already proposed possible solutions to this problem. These ideas include a new gearbox and a planetary gear system, which upon further consideration seem too complicated and pricey for this situation.

**Concept Generation and Selection**

The design team explored a number of different possible approaches to this problem. The gearing subsystem required some specific expertise. In order to better understand the requirements of the system, communication was opened with the sponsor and with local gear distributors and manufacturers. Several designs resulted, the most feasible of which being one including two worms in parallel and one with a double helical and spur gear concept.

**Parallel Worms**

This concept consists of two worms simultaneously being rotated by the drive shaft. One worm will have right hand threads while the other will have left hand threads. One of the two worms will be in
contact with the worm gear which causes the tines to rotate. To make the tines rotate the other way, the worms will rotate 180° to allow the oppositely-threaded worm gear to come in contact with the worm gear which will, in turn, cause the tines to rotate in the opposite direction.

![Figure 1: Parallel worms concept](image)

**Double Helical and Spur Gear**

In order to achieve the desired reversing feature, this design utilizes a collapsible shaft and an additional helical gear. A spur gear, with a diameter slightly larger than that of the current helical gear, is fixed to the tine shaft. The additional helical gear and another spur gear are located on shaft directly above the tine shaft with the spurs connected. When the user wishes to engage the reversing feature, he or she will cause the drive shaft to collapse and raise the worm, which will act analogous to a rack and pinion with the tine shaft freely rotating. The worm will eventually engage the upper helical gear. When the tiller is run in this new position, the worm will turn the upper helical gear and spur gear, which in turn will drive the lower spur gear and tine shaft in the reverse direction. A model of the design can be found below.
Comparison

Through communication with the sponsor, it was apparent that the most important metric was the dimensions of the transmission house. Too wide a transmission housing has deleterious consequences on the Mantis’ ability to till effectively. The concepts’ performance in this category helped drive the concept selection process. The double helical and spur gear concept was chosen as a result. The comparison of the two concepts based on width can be seen below. The parallel worm concept is shown on the left, while the “combo” gear concept is shown on the right.
The actuation subsystem for the dual helical and spur gear design was further divided into “collapsible” driveshaft and worm movement systems. The design will utilize a collapsible drive shaft in order to articulate the two helical gears. The design for a collapsible drive shaft involves the use of a DD shaft mating. A shaft containing the worm will articulate inside a drive shaft driven by the motor.

**Detailed Design**

The design team spent time more definitely realizing and developing the chosen concept into a full design, ready to be implemented into a *Mantis* tiller. After more consideration, the design team decided to add an additional subsystem to the design giving a total of three: the worm, worm gear, and spur gear system; the collapsible driveshaft system; and a new system including the method for articulating the collapsing driveshaft.

**Gearing Subsystem**

This subsystem incorporates the different gears that transmit power from the engine to the tine shaft. The worm meshes to either the upper or lower helical gear, which then turns the connected spur gear and, through the meshing of the spur gears, the other helical gear. The lower helical gear rotates, either directly from the worm or from its attached spur gear, and spins the tine shaft. Based on the sizing of the worm gears, the spur gears are easily chosen as having a 3in pitch diameter. Spur gears with a 3in pitch diameter are just large enough to maintain no interference between the worm gears and also easily manufactured as standard without requiring any custom gear requests.
“Collapsible” Driveshaft Subsystem

This subsystem employs a “collapsible” driveshaft in order to allow the desired axial motion of the worm. The shaft leading upwards from the worm mates with and is driven by the upper driveshaft through a DD shaft profile. The center of the driveshaft has a bored, hollow center using the same DD profile that allows the worm shaft to move up to three inches in the axial direction. The upper driveshaft mates with the engine through a hexagonal top profile, and is held in place by a tapered roller bearing press-fit into the housing.

![Figure 5: "Collapsible" driveshaft subsystem](image)

Worm Movement Subsystem

This subsystem is responsible for controlling the axial motion of the worm. A fork straddles the worm and moves in the axial direction along a low-profile linear bearing that is attached to the housing. The fork is moved up and down along guides located on top of the transmission housing, and is located and locked into place by a locking pin.

![Figure 6: Worm movement subsystem](image)
Full design

A model of the full design can be found below.

Figure 7: Full prototype design

Performance Validation

A prototype was built in order to prove the functionality of the proposed design. The transmission housing was modeled as a box, as seen in the design pictures above. One of the side plates was manufactured out of polycarbonate in order to see the gear work inside. The prototype was attached to a four-stroke Mantis engine and run at a low throttle. The engine was attached backwards from the conventional Mantis in order to better accommodate the pin-locking system on the top of the housing. The prototype can be found below.
After the prototype was built and proven to work as designed, it was validated to assess its performance in the metrics of success. Because the prototype was built as an aluminum box and not as a solid-piece casted housing like it would be when fully integrated into the Mantis product line, the weight and center of gravity metrics could not be directly measured. As a result, a solid model of a single-piece housing was designed and validated through SolidWorks. The model is found below.
The testing and validation focused on ensuring all of the metrics of success were met. The design can be considered a general success provided it meets or exceeds each of the target values. Each metric was evaluated and tested individually to determine if it fell within the acceptable range of target values.

**Gear Housing**

The gear housing width target value was set at 3.125 inches. The prototype housing width at its widest point was measured using calipers to be 2.55 inches. The proposed final casted housing modeled in SolidWorks was modeled to be 3.125 inches at its widest point to allow for maximum housing wall thickness while still remaining within the target value.

**Center of Gravity**

The acceptable rise in the center of gravity was set at 0.5in in order to keep the weight of the motor above the tines. Using element analysis in SolidWorks, it was possible to calculate the center of gravity of the transmissions. The center of gravity of the prototype was lowered 0.825in while the casted housing was lowered 0.755in, which are both acceptable values. The weight of the engine is more than the transmission housing. By increasing the weight of the housing below the motor, it actually lowers the center of gravity, which is highly beneficial for the Mantis in the proper tilling position.
Power Output

The desired power output was the current tilling output, with a maximum of 31ft∙lb of torque and 240RPM. Although additional gears were added to the transmission, the optimized gear ratio of 42:1 was kept between the worm and worm gear and the spur gears were matched to maintain identical speed between the two output shafts. Because of this matching, there is only a negligible frictional change to the power output in both the constructed prototype and the proposed single-piece housing.

Cost of Parts

Using the current cost of parts for the Mantis tiller, the cost of parts for the proposed design was speculated. The price of the current worm and housing were increased five and ten percent, respectively, in order to conservatively estimate the higher cost due to material volume increase for each part. The prices for the bearings, tine shafts, worm gears, etc. were taken as twice the current value, because the same parts can be used in the proposed design. The fork was estimated as half the housing cost, because it is anticipated that the fork will be formed by similar processes but contain approximately half the material volume. The price for the spur gear was estimated at half the cost of the worm gear, based off of estimates provided by gear manufacturers. A table of the anticipated cost of parts for the proposed design is found below.

Table 3: Estimated cost of parts for the final product

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Estimated Cost of Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worm</td>
<td>4.347</td>
</tr>
<tr>
<td>Thrust Bearing</td>
<td>0.42</td>
</tr>
<tr>
<td>Worm Gear (2)</td>
<td>15.68</td>
</tr>
<tr>
<td>Worm gear thrust bearing</td>
<td>0.376</td>
</tr>
<tr>
<td>Tine shafts</td>
<td>7.17</td>
</tr>
<tr>
<td>Tine shaft bushings</td>
<td>1.48</td>
</tr>
<tr>
<td>Tine shaft seals</td>
<td>0.06</td>
</tr>
<tr>
<td>Tine shaft seal retainers</td>
<td>0.208</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.078</td>
</tr>
<tr>
<td>Housing Cover</td>
<td>0.5</td>
</tr>
<tr>
<td>Transmission House</td>
<td>7.2853</td>
</tr>
<tr>
<td>Screws</td>
<td>0.124</td>
</tr>
<tr>
<td>Spur Gear (2)</td>
<td>7.84</td>
</tr>
<tr>
<td>Drive Shaft</td>
<td>1.587</td>
</tr>
<tr>
<td>Fork</td>
<td>3.64265</td>
</tr>
<tr>
<td>Fork Bearings</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>$52.00</strong></td>
</tr>
</tbody>
</table>

This proposed cost of parts list raises the cost of parts of the Mantis tiller by an estimated $25.65. This falls within the target value of raising the cost of parts by $34, further validating the design.
Cost of Assembly

The time of assembly for the proposed final product was estimated using standardized assembly time charts provided as supplemental material in MEEG304 – Machine Design: Elements, a junior-year design course in the University of Delaware Mechanical Engineering curriculum. Using these charts, the current Mantis transmission assembly was estimated to take sixty seconds. The new proposed Mantis transmission was estimated with an assembly time of ninety-five seconds. Using the current cost of assembly for a Mantis transmission, provided by Schiller Grounds Care as $14.48, the new transmission is speculated to incur an assembly cost of $23.00. This value falls within the target value of $25.00 for assembly ($10.50 above the current value) with some additional room for unseen assembly costs.

Number of Parts

The number of acceptable added parts was set at ten. This was easily calculated for both the prototype as well as the casted housing by simply comparing the finalized designs to the current tiller transmission. The prototype had twelve added parts. Although this is above the target value, different manufacturing processes account for the added parts in the prototype. In the final single-piece housing, both the linear bearing track and the fork pin posts will be part of the molded final housing. The fork and “T” will also be manufactured out of a single piece of material which makes the total number of parts nine, within the target value.

Weight

The target value for the largest acceptable weight addition was set as 5lbs. The prototype was weighed with a triple beam balance to obtain a weight of 8.25lbs compared to the current transmission weight of 3.5lbs, which is an addition of 4.75lbs. The weight of the casted housing model was estimated using SolidWorks element analysis as 4.98lbs. The additional material in the transmission housing makes the final model heavier. Although it is within the target value of 5lbs, it is very close. The design team will have to continue to work with Schiller in order to reduce this weight even further. Overall not all the target values were met for the prototype due to the limited availability of parts, machining techniques and time constraints. The proposed casted housing design meets all of the desired target values, however.

A table comparing the successes of the prototype and the casted housing in each of the metrics of success is found below.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Target Value</th>
<th>Prototype Value</th>
<th>Casted Housing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear housing</td>
<td>≤ 3.125in wide</td>
<td>2.55in</td>
<td>3.125in</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>raised ≤ 0.5in</td>
<td>lowered 0.825in</td>
<td>lowered 0.755in</td>
</tr>
<tr>
<td>Power output</td>
<td>31ft-lb, 240RPM</td>
<td>31ft-lb, 240RPM</td>
<td>31ft-lb, 240RPM</td>
</tr>
<tr>
<td>Cost of parts</td>
<td>≤ $60</td>
<td>N/A</td>
<td>$52</td>
</tr>
<tr>
<td>Cost of assembly</td>
<td>≤ $25</td>
<td>N/A</td>
<td>$23</td>
</tr>
<tr>
<td>Number of parts</td>
<td>raised ≤ 10 parts</td>
<td>+12 parts</td>
<td>+9 parts</td>
</tr>
<tr>
<td>Weight</td>
<td>raised ≤ 5lb</td>
<td>+4.75lb</td>
<td>+4.98lbs.</td>
</tr>
</tbody>
</table>
**Path Forward**

While the prototype was successful, there are several steps that must be taken before the project can be entirely handed over to Schiller. First, there are several aspects of the design that must be taken into consideration for changes between the prototype and their final production design.

**Single-Piece Transmission Housing**

Schiller has a patent on a solid transmission housing, which is very useful for the reliability of their transmissions. A one-piece housing protects the interior of the transmission from dirt and debris much better than multi-piece housings and also eliminates shearing in screws due to vibration. The design team has proposed a solid one-piece housing, but must further work with Schiller to ensure it is up to their specifications before this model is incorporated into the marketed Mantis.

**Worm**

Another design modification to be made comes with the worm. Due to time constraints and material availability, the design team had to manufacture a two-piece worm with a DD shaft lacking case-hardening. Because of this, no durability or reliability tests could be performed accurately. However, the team took the care to examine the reactions within the gear train. With the current 5mm shaft, assuming a worst-case SAE 1050 steel without case hardening, using Tresca failure criterion for the shear stresses in the shaft, the worm has a factor of safety of approximately 4.7. Although this value will increase with case hardening as the yield strength increases, this value does not model any impact loading or vibration fatigue in the housing. Schiller must examine the possibility of increasing the worm diameter while maintaining the proper 42:1 gear ratio. They must take care to find the balance between size, weight, and reliability for the marketed product. Additionally, the design team would suggest to Schiller to examine the possibility of reversing the handedness of the worm and worm gear and use the upper gear system for the normal tilling output. This would reduce the fatigue felt by the worm from the longer moment arm experienced in the lower meshed position.

**Optimization for Gear Sizing**

The design team decided to keep the spur gears at the same diameter, in order to keep the output the same in both the forward and reverse direction. If Schiller decides at a future point to increase or decrease the speed or torque of the reverse direction based on requirements for certain applications, the sizing of these gears can be changed and optimized. The only constraint to the sizing is that the distance of centers of the two gears is kept at 3in so that the worm gears do not interfere.

**Durability Testing**

As mentioned earlier, the design team was unable to do any durability or reliability testing based on time constraints. Schiller will still have to perform extensive durability testing of the new transmission design in order to stand by the warranties offered for their products. Conducting a string of long-term tests would allow them to confidently give consumers assurance in their products.
Control System

Once the design for the gearing and actuation subsystems is finalized, Schiller must focus on the control subsystem mentioned earlier. The control subsystem must be designed for the user interface with the tiller. Although the pin-locking mechanism currently on the prototype is a simple solution to the problem, it is not aesthetically pleasing. Schiller must spend some effort making their product more “user-friendly”.

Future Additional Considerations

There are other smaller considerations that must be taken into account before Schiller can incorporate the new reversing transmission into their Mantis product line. The assembly-line procedure must be changed. Different pneumatic presses must be designed to accommodate the new bearing locations and housing size. The assembly order must be modified as well, once the design is finalized.

In addition, before the reversing feature is marketed, Schiller must consider things such as safety manuals and instruction manuals for both Schiller employees and customers. Such things will ensure that Schiller makes the most out of their product in a safe and efficient manner.

Acknowledgements

The design team would once again like to thank Schiller Grounds Care for this great opportunity. Lana and Rick have been instrumental in their engineering advice, guidance, and support. Nina has been incredibly helpful in securing funds for the team’s design prototype and proof of concept. The design team has had a wonderful experience working with Schiller on this design and hope that it can be implemented into their product line in the near future.