**Title**

**Executive Summary**

The Tesseract Lobster is a mechatronics solution for the problem defined by Tesseract Power Co. It is capable of autonomously tracking the arena to find the tesseract and place it underneath the power pyramid, as required. Components were selected and designed with reliability as the top priority, and design constraints such as size were carefully followed. A four-wheel drive base with four inch wheels has been selected for stability and ease of control. A claw has been designed to detect and retrieve the tesseract, and a forklift with an intake mechanism secures the pyramid. These components were prototyped and tested individually, validating their effectiveness and the overall design of the Tesseract Lobster. To further improve the reliability of the product, powerful motors and sensors were selected and coupled with code for validation for each stage of the task. Implementation of all these components into a prototype gave insight on how these mechanisms should interact with each other, as well as the timeline required to materialize the finished Tesseract Lobster. The remainder of this report discusses the design process and the final product in detail.

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\*All figures referenced are in the Appendix

**Introduction**

The problem defined is to create an autonomous mechatronic system that retrieves a tesseract and places it underneath a power pyramid. The task is to be completed in a square arena with walls measuring 6 to 10 feet long and 3.5 inches tall, and conduits that must be maneuvered over. The tesseract is a magnetic cube with 0.75 inch side lengths, to be retrieved from a random location on the top of the arena wall. The power pyramid is 3 inches tall and has a square base with 4 inch sides. It emits an encoded infrared signal using LEDs, and has a square hole with 1.5 inch side lengths for the cube to be placed in. The task should be completed within three minutes, and the solution must be able to fit within a locker measuring 80x25x50 cm without disassembly.

To assist with designing and building a solution, groups were given VEX kits for prototyping and training with Solidworks and Arduino, as well as access to laser cutting and 3D printing services for custom parts.

The group identified the reliability of the solution to be most important, followed by task completion speed and size (see Figure 3 in Appendix for the full list of design specifications). Due to the nature of the problem and the size constraint of the solution, the group decided that a motorized robot was the best approach. The remainder of this report describes the process of designing the Tesseract Lobster according to specifications, construction of a prototype and its implications on the product, and the steps recommended to further improve the design.

**Discussion**

Customer Analysis and Functional Requirements

To understand what functional requirements the product should have and their relative importance, the customers of the product were identified. The problem defined by Tesseract Power Co. is very specific and warrants a solution that is appropriate only for this company and this task. This meant that the product will likely be one-of-a-kind, and implied that the reliability of task completion was far more important than the cost or simplicity of the design. It also meant that the product should not be designed for mass production.

There are currently no competitors or alternative solutions to this problem. This further supported the idea that cost is secondary to reliability, and all decisions were made with this implication in mind. Additional customer requirements were generated (Figure 1) with respect to the problem and customer defined.

The list of customer requirements provided the basis for generating functional requirements. Each customer requirement was translated into a distinct functional requirement that can be quantitatively evaluated and improved upon (Figure 2), such as completing the task within three minutes 100% of the time. The relative weighting of these requirements also gave insight on design priorities and is reflected in decision making throughout the remainder of this project (Figure 3).

Functional Decomposition

Next, the group broke down the Tesseract Lobster into smaller designs that can be integrated to solve the defined problem. It was decided that each sub-function in the functional decomposition of the robot should match an item in the breakdown of the problem (Figure 4). Upon consideration of how each subfunction needed to be achieved, the mechanisms for manipulating the pyramid and the cube were determined to be the most design extensive and prioritized as critical path.

The problem breakdown also served as a high-level programming structure. Subdividing tasks into modular functions allowed the function to be repeated until the robot is ready to move on. The robot can also check for problems before exiting the function, such as if it found and attempted to retrieve the tesseract, but could no longer find it after retrieval. Options for it to either try again or provide feedback to the user can then be implemented to improve reliability, instead of, for example, continuing to find the pyramid without the tesseract.

Initial Pyramid Retrieval Designs

The faces of a pyramid are not square with the base, greatly increasing the difficulty of retrieving and securing it. The design for a pyramid retrieval mechanism was developed before the tesseract retrieval mechanism in hopes of creating a single design that could manipulate both. The criteria for selecting the pyramid retrieval mechanism included a heavy emphasis on reliability. This is because the design is practically unjustifiable if it cannot function reliably, regardless of its other redeeming qualities. Size and speed were the next most important criteria, as the contribution to size from an individual mechanism is much smaller than that of the chassis, and the operating time of the robot retrieving the pyramid will be much less than the time it takes to locate it. Finally, complexity and cost were included as the least important criteria due to the customer analysis performed previously and the tendency for a negative correlation between these criteria and reliability.

The Claw design (Figure 5) involved linkages attached to the ends of a gear, which pull the claw together or push them apart when actuated by a motor, clamping onto the pyramid from above. Placing the linkages closer to the ends of the claw than the pivot allows a larger clamping force compared to having the motor at the pivot, and gives more space for the output gear to be geared down as necessary for more torque and even more clamping force. The biggest reason that a claw design was considered first was because of its potential to retrieve both the tesseract and the pyramid. It is also simple to construct and control as it only requires one stepper motor, which can lead to cost savings as well. The biggest issue with this design is its reliability, as it would pick up the pyramid using friction material at the tips of the claw. Not only are friction coefficients between materials difficult to determine, the contact area and orientation of the pyramid has a large effect on the outcome as well. Some suggestions to mitigate these issues included using suction cups or small vacuum pumps over friction material, but do not address the orientation problem and the overall reliability concerns.

The Roller Intake design (Figure 6) involved two gears with flaps attached to them that will rotate in opposite directions, which push the pyramid when placed between the gears. This mechanism is stationary and will lift the pyramid by pushing it up a ramp. The roller design solves the issue with the orientation of the pyramid, as the flaps can start intaking the pyramid as soon as contact with any surface is made. After testing a prototype (Figure 7), it was determined that the friction of the flappers was not sufficient to intake the pyramid unless the pyramid was pushed against some surface. Although this could be implemented by driving the robot into the pyramid and the design demonstrated an overall increase in reliability from the claw, the group continued to search for better alternatives.

The Arm Intake design (Figure 8) is similar to the Roller Intake design, but used angled solid rubber wheels instead of flaps to increase the normal force and friction. This design required some type of arm to lift the pyramid after retrieval as the wheels are much smaller than the flaps and closer to the ground. This meant an increase in complexity, as a lift needed to be designed and required an extra motor compared to previous designs. However, the benefits of having smaller wheels in direct contact with the pyramid allowed for retrieval without being pushed when in square orientation with the intake. Retrieval in other orientations were accomplished with less force pushing into the design as well, and was thoroughly tested on a prototype (Figure 9). This compact design also reduced size and allowed the pyramid to be securely located for interactions with the tesseract.

With these designs for the pyramid retrieval mechanism and weighted criteria in mind, a decision matrix consolidating their relative effectiveness was produced (Figure 10). The Arm Intake design was selected for its reliability despite the increased complexity in design and programming.

Initial Tesseract Retrieval Designs

As tesseract is much smaller than the pyramid and can be secured in a single interaction, the retrieval speed is less important than it was for pyramid retrieval. The mechanism will likely be an extension to the width of the robot if it drives along the walls, so the size of the design is more relevant than it was for pyramid retrieval. As before, reliability is the top criterion, while complexity and cost are least important to the success of the design.

The Intake design for the pyramid was re-evaluated in an attempt to make it appropriate for the tesseract pickup as well. Some suggestions included changing the angle of the wheels or adding magnets. Although it was possible to lift the intake up to the height of the wall, no solution was found to align the intake wheels with the top of the wall without interfering with it, and would have to be mounted on the side of the robot creating difficulty for driving into the pyramid. Although merging the retrieval mechanisms would simplify the robot overall and reduce cost, the compromise in performance and reliability made this option difficult to justify.

The Arm Claw design (Figure 11) was similar to the VEX claw on a smaller scale. The arm would be mounted on the robot at the same height as the wall, and can pivot to adjust for minor height deflections. The claw design is much more reliable than the intake for picking up and securing the tesseract, and the arm can rest over the wall while the robot drives along the perimeter of the arena. It is also quite simple to construct and operate, and could be lowered to release the tesseract at a lower height for interaction with the pyramid. This design was tested on a prototype (Figure 12), and the claw was verified to secure the tesseract reliably. However, it was also found that the motor controlling rotation of the arm was unable to stay powered and hold the arm in a horizontal position for an extended amount of time. The tesseract also bounced to a larger range of positions than expected even at very low release heights. Although the claw design was proven to be successful, the manner in which the arm is held and the tesseract is placed required redesign.

The Rail Claw design (Figure 13) utilized the same claw design as the previous, but retracted and extended the claw by mounting it at the end of a rack and pinion. The tesseract would be retrieved and controlled by retracting the rack and dropping it in a funnel on the robot. This eliminated the problems of powering a motor to hold horizontal position and the tesseract bouncing randomly, increasing the reliability of the entire procedure. The vertical adjustability of the arm has been removed to increase the stability of the design, but the variation in wall height was small and did not affect results during testing. Similar to the Arm Claw, the Rail Claw was also verified to be effective through testing of the prototype (Figure 14).

The Magnetic Intake design (Figure 14.5) was a completely different approach where a rotating mechanism brushes flappers with magnets attached over the wall. The tesseract will be secured by magnetic attraction forces after coming in range of the intake. Although simple in theory and effective, this design requires some method of indicating when the tesseract has been collected and a reliable way of removing it from the intake. It is also much larger than the other designs and more complex to construct, but requires one less motor and can be easier to control.

A decision matrix with the re-weighted criteria was created to evaluate these options (Figure 15). The Rail Claw was chosen for its overall reliability improvements over the Arm Claw.

Chassis Design

The main functions of the chassis for the Tesseract Lobster are to provide a basis for mounting the aforementioned designs and maneuver around the arena, while following the size constraint. Larger 4 inch rubber wheels have been selected assist with driving over conduits and reduce slipping. Similar to a tank, a four wheel drive system where the wheels on either side turn at the same speed has been selected for stability and ease of control. Additionally, the output wheels will be geared down by a factor of 6 due to the torque specification of reasonable motors (Figure 15.5). A rectangular base that is large enough to accomodate the drivetrain was designed out of aluminum parts, and space has been allocated in the middle and on the guard rails for mounting mechanisms and sensors. This design was prototyped using standardized VEX components due to ease of assembly (Figure 16).

Electrical Component Selection

To ensure that the Tesseract Lobster has the information and actuation it needs to complete the defined tasks autonomously, careful consideration has been given in selecting the appropriate electrical components. The Nucleo 64 STM - F446RE has been selected as main MCU for the product due to having a 180 MHz clock cycle, which operates more than 500% faster than the MSEDuino (Figure 17). This allows for faster processing and refreshing speed, which translates to faster response time and reliability during operations. ST LSM303 and NXP MAG3110 magnetic sensors have been selected for locating the tesseract over the hall effect sensors due to having superior range and 3D readings. Two TSOP32338 IR sensors were used to locate and decode the signals emitted from pyramids, one shrouded and one unshrouded for coarse/fine adjustment. 72 in. oz. motors were selected for the product, as they provide sufficient torque to lift the pyramid intake mechanism and drive without slipping, and accounting for factor of safety (Figure 17.5). Limit switches in addition to mechanical stops will be used to ensure that the pyramid and tesseract arms reach fully extended and retracted positions with consistency. Three VEX Ultrasonic Rangefinders will be used for distance, one in the front for turning and two on the right for driving parallel to the wall. Finally, an ESP8266 WiFi Module will be implemented on the product to wirelessly receive commands and update status to the user. The list of electrical components can be found in Figure 18.

Prototype Development and Testing

The integration of all the components selected and designed above into a functional prototype verified some components, and helped find room for improvement in others. The group was able to successfully retrieve the pyramid through the pyramid intake prototype made out of VEX plates and brackets. It was then discovered that no good way of mounting the intake to the chassis has been designed yet, and the metallic VEX parts were both heavy for the motor and attracted the magnetic tesseract. This was especially a problem for the bottom “forklift” piece of the intake, as it needed to be thin to wedge underneath the pyramid and strong enough to hold it. Alternative materials considered for this piece included wood, aluminum, acrylic, and finally carbon fiber was selected as it met the requirements. Remaining components of the intake were also replaced with a combination of custom cut acrylic pieces and aluminum brackets, and mounted to the chassis using a parallelogram four bar linkage design to increase stability. All holes and fasteners used were in compliance with VEX standard 8-32 size for ease of manufacturing and assembly.

Testing with the drive base showed problems with maneuvering over conduits, as the wheels slipped and the motors stuttered. This showed that better motors and wheels were likely needed to provide the necessary amount of power and friction for the robot. To combat these issues for the prototype, grip tape was applied to the wheels to increase friction and alternative motors were sourced. Although the new motors seemed to run better, it was not compatible with the established drive base. A gear train with a mechanical advantage of 6 was implemented instead to amplify torque over speed.

Necessary sensors for the prototype were tested thoroughly to understand the capabilities of the Tesseract Lobster. The hall effect sensor provided was first tested to verify the decision to use a magnetometer instead. It produced significant readings only within one or two centimeters at a specific orientation to the tesseract, and was quickly replaced by the magnetometer. The magnetometer has a much higher range, detecting the cube from more than five centimeters away, and can be mounted high enough to always give consistent readings. The IR sensors were tested next, and the unshrouded sensors were found to only have a range between one to two feet depending on the strength of the transmitter and a massive field of view of 135 degrees. The shrouded IR sensors have even less range of around one foot and has a field of view of less than a degree, which is unreliable for pinpointing the pyramid since the emitted signal toggles on and off. These polarized sensor capabilities forced the team to replace the shrouding, and a metal pipe was used instead to change the field of view to around 10 degrees. The group had experience working with ultrasonic sensors and the robot was able to drive parallel to the wall very early on.

Minor improvements during the prototyping process include replacing gears and VEX brackets that constituted the claw to a single custom acrylic piece. This modification allowed for reduced number of parts and increased mechanism stability. Insulating pieces were used to mount the MCU to prevent shorts and careful cable management reduced the risk of getting caught by moving components. CAD of the prototype can be found in Figure 19.

Code Development

A block diagram of how the MCU communicates with the rest of the robot was created soon after mechanical and electrical components were finalized (Figure 20). Individual pieces of test code were written for testing each sensor and section of the problem breakdown (Figure 21). It was decided that object-oriented programming practices should be implemented and a robot class was developed so code can be written in similar fashion to C++. The strategy for completing the task that the code attempted to execute started by moving the robot forward with the claw fully extended until the front ultrasonic sensor detected a wall. It then turns left about its axis until the front senses a far distance, and the robot moves towards or away from the wall as it drives forward depending on the distances of the rear right and front right sensors. The front sensor continues to poll for distance and issues a left turn when the wall is close. The magnetometer polls for the tesseract as the robot drives beside the wall, and the claw will close when the reading indicates that the tesseract is within grasp. The robot then moves back and forth as it systematically scans the arena using the unshrouded IR sensor on the front, and drives without bumping into walls using the front ultrasonic sensor. Once the unshrouded IR sensor picks up the signal from the pyramid, the robot turns about its axis and pinpoints it using the modified shrouded sensor on the rear. The pyramid intake mounted on the rear is then lowered and the robot reverses into the pyramid while the intake wheels push the pyramid into the mechanism and triggers a limit switch. The intake then lifts the pyramid and the cube is dropped into the funnel and lands underneath the robot. Finally, the robot drives forwards and lowers the lift over the cube, and the intake wheels reverses the pyramid out to complete the task. A more elaborate code flowchart can be found in Figure 22.

Although code for individual components were tested and verified, logic for the entire sequence of the task has not been completed. The current progress of the prototype cannot serve as validation that the product solves the defined problem. Accurate evaluation of the effectiveness of the product requires more time for code implementation and testing.

Final Product

The prototype closely reflects the functionality of the actual product, with a few key differences. Machined 1060 aluminum pieces are used to avoid attraction to the tesseract and reduce fasteners, instead of metallic VEX components. Wheels with good treads and friction characteristics are selected to improve drive control. 72 in. oz. motors will be used to further improve drive and accuracy of retrieval mechanisms, and is justified by the poor performance of the VEX motors. The rack and pinion can also rotate normal to the ground on top of translating outwards so it can drop the cube into a funnel closer to the pyramid intake and improve the reliability of the interaction. Rigid aluminum bars that can support the load of the intake are designed to reduce complexity. Finally, security features such as limit switches will be implemented onto moving components to ensure they extend and retract to proper positions without stalling and damaging the motors. See Figure 23 for CAD of the final product.

Code for validation will be implemented into the final product, where the robot can re-attempt a part of the task if it determines that it has not been completed correctly. A Wifi module will also be implemented allowing for wireless commands and feedback.

**Conclusions**

The Tesseract Lobster abided by the constraints established and was designed with reliability as the priority. This is evident in the amount of consideration given to the construction of both the prototype and the final product. The increased reliability also caused a trade-off in simplicity, which led to incomplete implementation of the prototype code at the showcase. Subfunctions of the robot, such as sensors, intake mechanisms, and some sections of the task breakdown were tested and validated. This implies that the design is heading in the right direction and gives confidence for the effectiveness of the product. The overall effectiveness of the design requires implementation of the prototype code to be evaluated properly. Areas of improvement continue to emerge through the iterations of design performed, in an effort to create a reliable final product.

**Recommendations**

Although unsuccessful in completing the task at the showcase, the prototype constructed gave insight on areas of improvement for subsequent iterations. The main issue with the prototype that prevented the successful completion of the task is code implementation, and the timeline for prototype development should be extended and monitored. Testing should also be done more thoroughly to optimize trigger and tolerance thresholds for sensor data and time count for motors. Testing of motors with more power and wheels with better friction characteristics should be conducted to verify the component selection of the product. Finally, the interaction of the claw and the pyramid intake should be re-evaluated, and a degree of rotation normal to the ground can be implemented on the rack and pinion so the claw can release the tesseract closer to the intake.

Some additional suggestions outside the design constraints can be explored to solve the pathing issue. Both the magnetometer and IR sensors could not detect the appropriate signals beyond a small distance. This is largely due to the weak magnetic field of the tesseract, the rapidly decaying nature of magnetic fields, and the weak transmission properties of the LEDs on the pyramids. It forced the robot to pick a random starting point and systematically scan the appropriate region to look for the item, which is inefficient and operating time increases significantly if the field was expanded. This is not a simple issue to be solved with “better sensors”, and solutions such as image tracking and LIDAR area mapping have been suggested. These options were not explored during the design process as they do not meet the constraints established, but should be considered if the Tesseract Lobster is expected to be even more reliable and efficient. A block diagram of possible components for this solution can be found in Figure 24.

**References**

**Appendix**

Figure 1: QFD Customer Requirements

Figure 2: QFD HOQ

Figure 3: QFD Functional Requirements

Figure 4: Design Review 1 Summary

Figure 5: Pyramid Claw CAD

Figure 6: Roller Intake CAD (Lovdeep’s)

Figure 7: Picture of ^ prototype

Figure 8: Arm Intake CAD (Maral’s)

Figure 9: Picture of ^ prototype

Figure 10: Decision Matrix For Pyramid Retrieval Mechanisms

Figure 11: Arm Claw CAD (Fan’s)

Figure 12: Arm Claw pic prototype

Figure 13: Rail Claw CAD

Figure 14: Rail Claw pic

Figure 14.5: Magnetic Intake CAD

Figure 15: Decision Matrix For Tesseract Retrieval Mechanisms

Figure 15.5: Drive Motor Calculations

Figure 16: Chassis CAD

Figure 17: STM and MSEDuino Comparison

Figure 17.5: Lift Motor Calculations

Figure 18: Product Electrical Components

Figure 19: Prototype CAD

Figure 20: Block Diagram For Prototype

Figure 21: Various Test Code

Figure 22: Code Flowchart

Figure 23: Final Product CAD

Figure 24: Potential Improvements Block Diagram