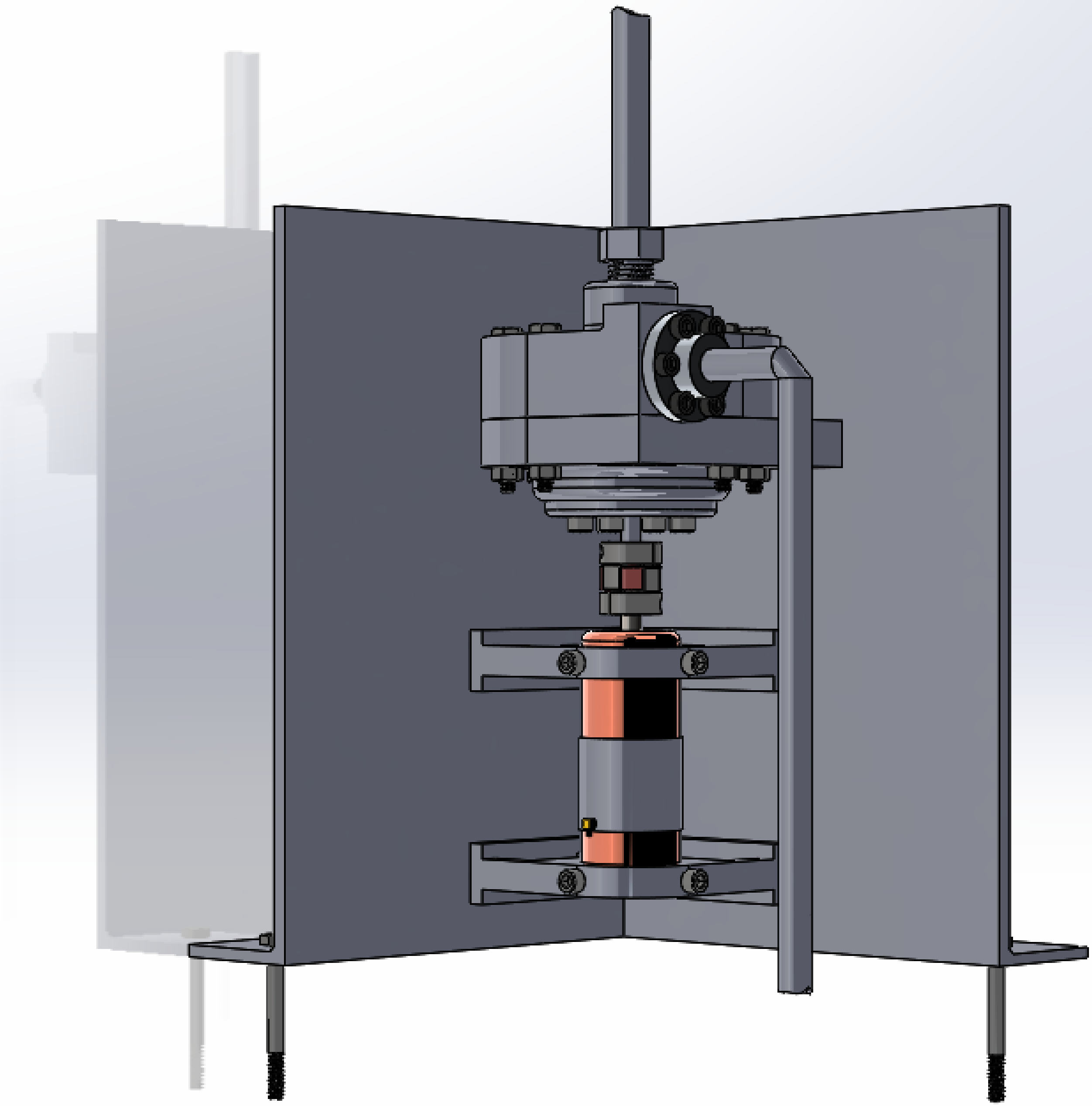
ME 492 | Winter 2019

Progress Report



Flight Ready Electric Feed System

Sponsored by Portland State Aerospace Society (PSAS)

TEAM MEMBERS:

Julio Garcia
Philip Wahl
Jonas Mendoza
Nick Sheldon
Henry Ju
Shayli Elrod

ACADEMIC ADVISER:

Baldur Steingrimsson

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Executive Summary

Portland State Aerospace Society (PSAS) aims to design, build, and test an Electric Feed System (EFS) prototype using commercial off-the-shelf parts and in-house manufacturing. Currently, CAD designs have been finalized and selection for several key components have been chosen including the impeller design and shaft connection, motor, and design for the pump housing. This report details the requirements and selection process criteria for these components. Progress on detailed design is also discussed.

1 Introduction

Portland State Aerospace Society (PSAS) requires a Flight-Ready Electric Feed System for their liquid propellant rocket, Launch Vehicle 4 (LV4). An Electric Feed System (EFS) is a series of pumps used to deliver liquid propellant to the rocket engine a specified pressure. One of the two EFS pumps must be cryogenic compatible to withstand the liquid oxygen (LOX) environment. The second pump must be compatible with isopropyl alcohol (IPA). In traditional amateur rocketry, a high pressure "blow down" pressure tank system is used to deliver propellant to the engine. A successful EFS design will provide PSAS with a low-cost, low-weight alternative to a pressure tank for LV4, making it possible for the rocket to achieve the target goal of 100 kilometer launch capability.

2 Mission Statement

The Electric Feed System Capstone aims to provide affordable, lightweight propulsion system technology, increasing the capabilities of amateur rocketry and student education.

The final system delivered to PSAS is expected to be tested for chemical compatibility, operating temperature conditions, performance efficiency, vibrational disturbances, and control signal data. PSAS also expects complete documentation of background research, theory of operation, pump system CAD models, safety analysis, and standard operating procedures for mounting and operation. Final deliverables must be within budget and completed by June 2019.

3 Project Design Specification (PDS)

Portland State Aerospace Society has defined the requirements for the EFS capstone. Table 1: *Product Design Specifications* summarizes the customer needs and their ranking of priority upon final completion. Table 2: *Customer Requirements*, and Table 3: *Engineering Requirements* cover targets and metrics, along with our verification process for achieving these goals.

Table 1: Product Design Specification

Product Design Specification (PDS)			
Customer Need	**Primary Customer**	**Priority**	**Time**
Must be tested with liquid Nitrogen (LN2) and isopropyl alcohol (IPA)	PSAS	5	*****
Must safely keep the propellants separated at all times	PSAS	5	*****
Should have embedded sensors for data acquisition	PSAS	5	*****
Should have emergency shut off procedure and battery cutoff	PSAS	5	*****
Should have embedded sensors for feedback, and control	PSAS	4	***
Must deliver propellants at 450 PSI with NPSH of 45-100 PSI.	PSAS	4	***
Must be able to operate for multiple engine test fires (≥ 10 firings) without system overhaul	PSAS	3	****
Must handle launch module vibration and 10g's acceleration for 20 seconds.	PSAS	3	***
Must be compatible with liquid oxygen (LOX)	PSAS	3	*****
Should minimize system plumbing losses (major and minor)	PSAS	2	*
Must be able to be used on the PSAS engine test stand	PSAS	1	****

Table 2: Product Design Specification

Customer Requirements							
	Requirements	**Primary Customer**	**Metrics & Targets**	**Metric**	**Target**	**Target Basis**	**Verification**
Performance	LN2 Compatibity	PSAS	Must be able to safely pump liquid nitrogen	N/A	No damage	Customer Defined	Cold flow testing
Performance	Fluid Separation	PSAS	Must restict fluid mixing even in the event of failure	N/A	No fluid mixing	Customer Defined	Prototyping
Installation	Manpower to test	PSAS	Manpower	# People	4 People	Customer Defined	Cold flow testing
Installation	Time to replace spare parts	PSAS	Time	Mins	2 Hours	Team Defined	Timed after prototype built
Safety	LOX Safety	PSAS	Design with all chemical safety requirements via B11 Training	N/A	No LOX hazards	Customer Defined	Cold flow testing
Safety	Electrical Safety	PSAS	Ensure all controls systems are safe from fluids, etc.	N/A	No electrical hazards	Customer Defined	Prototyping
Maintenance	Minimal upkeep between test fires	PSAS	No overhaul to be required between tests	Hours of Work Rqr'd	< 4 hours	Group Defined	Testing
Maintenance	Replaceable Parts	PSAS	Readily Available Parts for replacement bearings, rings etc.	N/A	Off the Shelf Parts	Group Decision	Budget
Cost	Minimal production cost	PSAS	Cost	Dollars	< $9,500.00	Customer Defined	Budget

Table 3: Product Design Specification

Engineering Requirements							
	Requirements	**Primary Customer**	**Metrics & Targets**	**Metric**	**Target**	**Target Basis**	**Verification**
Performance	EFS size	PSAS	Must be able to fit within LV4 rocket module	inches	11.3"	Customer Defined	Airframe simulation
Performance	Repeatability	PSAS	Reusable for 10 test fires	# Fires	10	Customer Defined	Failure testing
Performance	Pressure Gain	PSAS	Must achieve target pressure differential	psi	350	Customer Defined	Cold flow testing
Environment	Withstand Launch Environment	PSAS	Maintain operation during launch conditions	g	10	Customer Defined	Testing
Environment	Withstand vibration of Airframe	PSAS	Components must be designed to avoid harmonic frequency of rocket structure	Hz	TBD	Customer Defined	Simulation

4 Project Planning

To promote progress in all divisions of the EFS design, the team was divided into two groups. The first group's efforts were focused on finalizing design and the controls for the motor. The second group began prototyping the IPA pump housing, impeller, and motor mounts. To assure members of the team had clearly defined tasks and were able to meet deadlines, a Gantt chart was created. Table 4 illustrates the timeline of completion while highlighting priority and the individuals assigned to each task.

5 External Search

The primary focus for the winter term was to design and test the pump optimized for IPA. In order to progress toward this goal, impeller and housing designs had to be selected and optimized. Additionally, motor selection was required to meet calculated specifications.

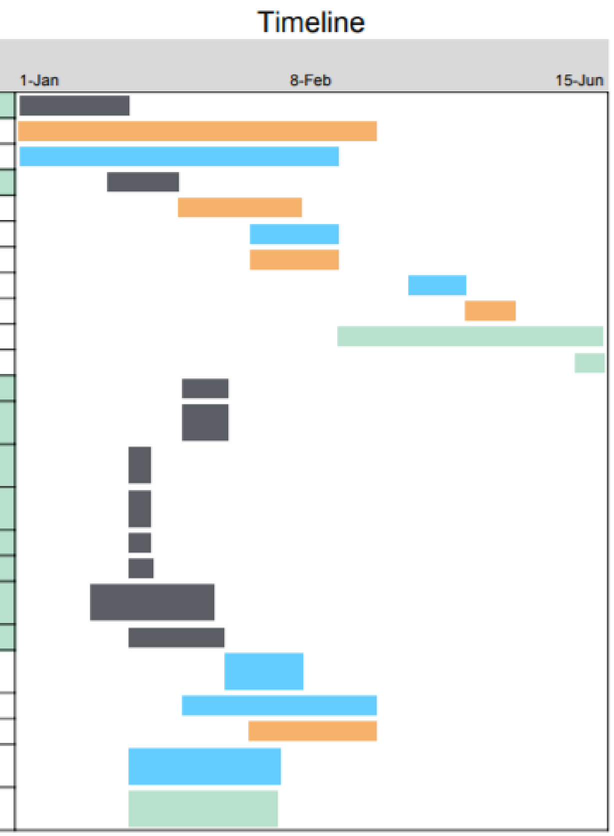
5.1 Impeller Design

In EFS pumps, a specialized impeller is required to provide high pressure gains while maintaining a low flow rate. Since this project is a part of an iterative design spanning multiple capstones, the design process began by referencing the previous capstone team's work. The research performed for the first EFS iteration found that a Barske impeller is the most ideal design for this application. The unique vane pattern of these impellers can be seen in Appendix B, Figure 3b. Industry literature on liquid propellant rockets verified that Barske impellers are generally used for the target pump curve. The vane patterns of Barske impellers are intentionally designed for less fluid flow. This inefficiency in flow allows for large pressure gains while maintaining low flow rates. The previous team also tested a variety of impeller designs with varying number of vanes. It was found that 10 vanes resulted in optimal pressure gains while maintaining desireable motor performance.

Table 4: Electric Feed System Project Schedule

Legend	
Low Priority	
Medium Priority	
High Priority	
Completed Task	

Task	People	Priority	Start Date	End Date	Days Left	Status
~~Concept Design IPA Pump~~	All	High	~~1/1/2019~~	~~2/1/2019~~	~~-39~~	Completed
Concept Design LOX Pump	All	High	1/1/2019	4/12/2019	31	Incomplete
Control System Design	Julio, Nick	Medium	1/1/2019	4/1/2019	20	Incomplete
~~IPA Pump Prototyping~~	Jonas, Nick	Medium	~~1/26/2019~~	~~2/15/2019~~	~~-25~~	Completed
Manufacturing IPA Pump	Jonas, Nick, Shayli	High	2/15/19	3/22/19	10	Incomplete
Testing IPA Pump	All	Medium	3/7	4/1/19	20	Incomplete
Control System Testing	All	High	3/7/19	4/1/19	20	Incomplete
Testing LOX Pump	All	Medium	4/21/19	5/7/19	56	Incomplete
Full System Test	All	High	5/7/19	5/21/19	70	Incomplete
Final Write Up	All	Low	4/1/19	6/15/19	95	Incomplete
System Demonstration	All	Low	6/7/19	6/15/19	95	Incomplete
~~Motor Selection~~	Phil, Julio	Medium	~~2/16/19~~	~~3/1/19~~	~~-11~~	Completed
~~IPA Shaft & Impeller Material Selection~~	Henry, Nick	Medium	~~2/16/19~~	~~3/1/19~~	~~-11~~	Completed
~~Purchase DAQs and Pressure Transducers~~	~~Tim, Julio~~	Low	~~2/1/19~~	~~2/7/19~~	~~-33~~	Completed
~~Purchase Tachometer and Temperature Sensor~~	~~Julio~~	Low	~~2/1/19~~	~~2/7/19~~	~~-33~~	Completed
~~Purchase Flow Meter~~	~~Julio~~	Medium	~~2/1/19~~	~~2/7/19~~	~~-33~~	Completed
~~Finalize Shaft & Impeller CAD~~	~~Phil~~	Low	~~2/1/19~~	~~2/8/19~~	~~-32~~	Completed
~~Finish machining impeller / shaft for open tank testing~~	~~Nick, Jonas, Shayli~~	High	~~1/21/19~~	~~2/25/19~~	~~-15~~	Completed
~~Run open tank test~~	~~All~~	Medium	~~2/1/19~~	~~2/28/19~~	~~-12~~	Completed
Finalize CAD designs based on open tank test results	Phil	Medium	2/28/19	3/22/19	10	Incomplete
Begin FEA Analysis for LOX Pump	Nick, Julio	Medium	2/16/19	4/12/19	31	Incomplete
Test IPA Rev 1	All	High	3/7/19	4/12/19	31	Incomplete
Complete CFD analysis for LOX pump	Phil	Medium	2/1/19	3/16/19	4	Incomplete
Finish Progress Report - Winter Term	All	Low	2/1/19	3/15/19	3	Incomplete



5.2 Motor Selection

The previous EFS capstone team found that the motor needed to provide high rotational speeds compared to standard pumps. Additionally, the motor had to be capable of quickly and accurately responding to flow characteristics via a feedback control system with integrated sensors. The first EFS design found successful results with the use of a high output RC boat brushless DC (BLDC) motor. However, comparing system requirements showed the need for more power and control than previously achieved. Through fluid flow and geometric calculations (Appendix A), approximately 2 kW of power, 0.6 $N \cdot m$ of torque, and $30,000$ RPM were identified as the factors for motor selection.

5.3 Pump Housing

A key feature carried to the new design from the first EFS iteration was the pump housing. The housings in both the original and current iteration feature sections that come together axially. This allows for easy assembly and manufacturability. The current design for the housing can be seen in Figure 1. The current challenge was the reduction of weight and bulk of the first iteration. A soft goal requested by PSAS was for the EFS to be flight-ready, making weight reduction a target for this design. Shape and material are being continually evaluated to determine if any sections of the housing can be altered.

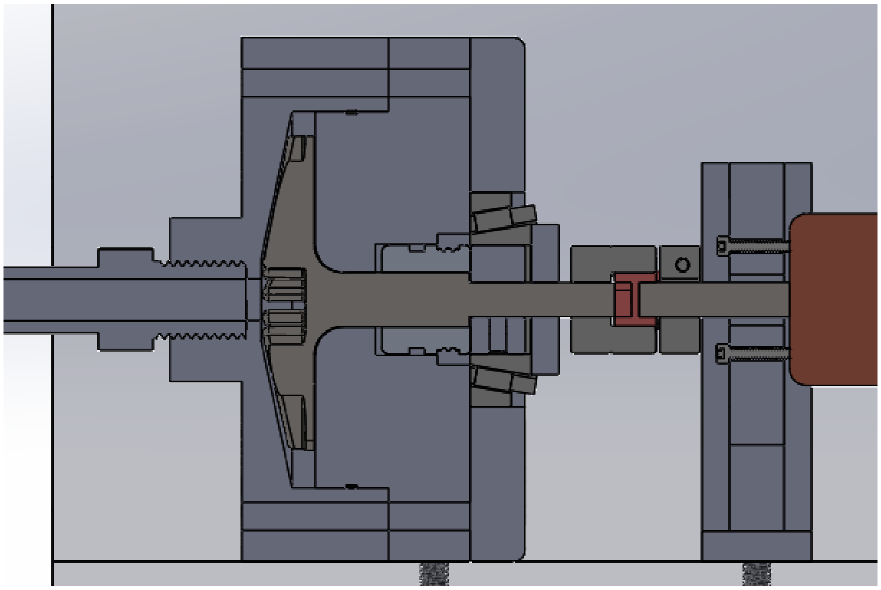


Figure 1: Cross-Section of Current Pump Housing Design

6 Internal Search

Weekly meetings were held during the design phase where sketches and CAD models were displayed regularly for the group to evaluate. This dedicated time gave teammates an opportunity to express concerns in design, and ultimately allowed the group to collectively agree upon the final designs for given components.

6.1 Impeller Design

The previous team's impeller was manufactured using direct laser metal sintering (DLMS), an additive manufacturing process. While this process allows for complex geometry that is often difficult or impossible to create with conventional machining processes, it cannot achieve the high dimensional precision that machining allows. Additionally, due to the nature of metal sintering, parts produced via this method are more porous than parts machined from solid billet. This became an area of concern for the team for two reasons.

In order for the impeller to function properly, it must have a very small clearance between the pump housing and front face. The smallest of these clearances in our design is 0.008 inches. The dimensional resolution possible with DLMS was deemed too unreliable, as the tolerance on these parts may allow the impeller to contact the wall of the impeller chamber. Further, geometric inconsistency would likely cause the impeller to become unbalanced when rotating at the $30,000+\ rpm$ required for our design. Second, the porosity present in sintered parts was of concern considering the impeller would be rotating at high speed. While the system is only expected to transmit approximately $0.6N \cdot m$ of torque through the impeller under steady-state conditions, porosity could allow cracks to form and propagate throughout the impeller geometry under operating conditions. Catastrophic failure will occur in the rocket should the pump impeller fracture during flight operation. Fragments of material entering the fuel line would also result in launch failure. Taking these conditions into consideration, the team decided to move forward with machining the impeller in-house, using the CNC machines available on campus.

Once the impeller material and manufacturing processes had been reviewed, the team began to analyze potential designs for mating the pump shaft with the impeller. The previous team incorporated a small hub on the backside of the impeller that had a hole bored out for the pump shaft. A pin was inserted into matching cross-holes on the hub and shaft in order to connect the two components. Our team had some concern with this design and whether or not it may actually weaken the shaft, given the cross-hole diameter was relatively large compared to the shaft diameter. The reduction in shaft cross-section could introduce stress concentration problems if the inserted pin didnt create a tight fit. The team began to analyze alternative methods to connect the shaft to the impeller.

The first alternative to using a pin was to create a lobed shape on the end of the shaft, that would fit into a mating hole in the hub of the same shape. This design would allow the shaft to spin the impeller without slipping, since the shaft would only connect to the hub in one orientation. A lobed shape was preferred for this design since it would remove sharp edges, and thus stress concentrations, in both the shaft and hub. However, the team realized that this design would not prevent the impeller from sliding forward on the shaft in the axial direction, allowing for potential contact with the front of the impeller chamber. In order to prevent this motion, a set screw or pin would need to be incorporated, further weakening the design. Additionally, a lobed shape would introduce complexities in the manufacturing process.

The next shaft-impeller design explored used a keyed shaft. In this design, a shallow rectangular slot would be cut on the outside diameter of the shaft in the axial direction. A matching slot would be cut inside the hub's bore, and a rectangular key would be used to fill the space between the shaft and hub. This would allow the shaft to spin the impeller. This design can been seen in Figure 2a. It was determined that this design would also require the use of a set screw to prevent the hub and shaft from separating. However, the set screw could simply pass through the hub to press down on the key. Doing so would not require any additional features to be cut onto the shaft, thus maintaining the integrity of the shaft.

The challenge with the keyed design became apparent when the required machining process was taken into consideration. While a slot could easily be cut on the shaft, we would need to broach the hub in order to cut the mating slot. Broaching, a process in which small amounts of material are sheared away, requires very specific tooling to be performed inside a blind hole. Since this tooling isn't readily available on campus, the team would need to purchase the supplies. The required tooling to broach just the hub slot would have cost around $450. Further, a broaching operation requires a groove to be cut deeper inside the hub bore to provide relief for chips formed during the broaching operation. Otherwise, the tool will bind up and break. This relief groove would require the purchase of additional tooling, and significantly weaken the hub. The team decided that prototyping this design would be too expensive, and would potentially result in a weaker assembly than the previous two potential designs (pin and lobe).

Taking into consideration the possibility of inefficient torque transmission from the motor to impeller (due to various connections between components), alternative designs were considered. The idea of using a solid state impeller-shaft design was suggested, in which the impeller and shaft would be one single component. Combining the shaft and impeller removes the need for a hub. Without the hub, this design would allow material reduction on the impeller itself. Additionally, it would allow the pump housing the be thinned, resulting in a more significant reduction in weight. Concerns with the design arose when considering the change in diameter from the shaft to the outer diameter of the impeller. The largest diameter of the impeller is around 8 times larger than the shaft diameter. It was a concern that stress concentrations at the shaft-impeller interface could lead to failure. The team reviewed the torque requirements and the material properties of AL 6061-T6, and determined that the low torque should not be enough to cause failure. However, to further reduce the possibility of failure, a large fillet was placed at the shaft-impeller interface. This resulted in a less drastic transition in diameters.

Ultimately, it was decided that the solid state shaft-impeller design was the most promising option. This assumption was then verified with design scoring metrics before moving forward with prototyping.

6.2 Motor Selection

The requirements for shaft power led to the selection of a TP Power 4070CM as the BLDC motor. A Swordfish 200A electronic speed controller (ESC) was also selected to interface with the motor. The motor, controller, batteries and sundries were within budget at less than $1000. The motor comfortably exceeded the requirements for the IPA system. By allowing replication of the power system to the cryogenic pump, purchasing an overpowered motor for the IPA pump increased design efficiency. The use of identical motor systems for both pumps saved time and freed up focus for other components.

When selecting the ESC, batteries, and connectors, safe autonomous operation during flight was prioritized by PSAS for the team. Gold plated, 8mm bullet connectors were used along the entire wire harness, operating with a safety factor of 1.75 against high current load damage. This minimizes the risk of meltdown and electrical fires. The batteries powering the motor have a 350A capable discharge rate, which provides a 1.88 safety factor. The Swordfish 200A ESC provides a built in water cooled case for heat dissipation, with a safety factor of 1.34 against damage from high current.

6.3 Pump Housing

It was determined that the front case of the housing needed to be machined on three of its sides. Being limited by a three axis vertical mill, the profile of the front case was modified to have flat surfaces that allowed a secured set up for the side operation. CAD/CAM simulation models helped determine the dimensions of the flat without sacrificing wall thickness. Pipe thread analysis[2] contributed to the selection of main hardware for the housing and plumbing connections.

Alignment between front and back housing cases when assembled was a concern, and two solutions to approach this issue were evaluated. The first solution was to use small dowel pins press fitted on the front case, allowing the back case to align itself to the front case when assembled. This solution was supported by previous successful results from past projects under similar conditions. The second solution was to machine oversize holes on the front case and to use precision shoulder bolts that would allow the back case to slide in place using the ground shoulder as a guide. Based on the hardware specifications provided by the manufacturer, the team concluded that the precision shoulder bolts would be the best solution due to the tolerance and surface finish of the ground shoulder bolts. The time saved by eliminating extra machining operations also supported this decision.

7 Final Design Evaluation

Criteria influencing decisions made to move from design to prototyping were thoroughly evaluated and compared against customer and engineering requirements. For complex design selections, scoring matrices were used.

7.1 Impeller Design

The impeller and shaft connection interface selection required careful evaluation and consideration of five key criteria. One of the highest ranking criteria was the ability of the impeller and shaft to survive up to 1.1 $N \cdot m$ of torsional forces during high speed rotation up to $30,000$ rpm. Further, the system needed to remain balanced while in motion.

The impeller and shaft needed to be machinable by the equipment and tooling that were available within the campus machine shop. These requirements were defined by the two-axis CNC lathe and the three-axis CNC mill. The tooling cost for each design was also ranked. Lastly, robustness was defined as a criteria to account for the potential of cracking, bending, or other physical deformations.

These criteria, along with the score for each design, is shown in Table 5.

Table 5: Impeller Design Concept Scoring

Criteria	Scale (1-10)	Single-Piece (0-1)	Key Slot (0-1)	Lobe (0-1)	Dowel Pin (0-1)
Torque Capability	10	1	1	0.7	0.7
Rotational Balance Speed	8	1	1	0.6	0.8
Machinability	10	0.7	0.6	0.7	1
Tooling Cost	5	0.8	0.5	0.8	0.8
Robustness	7	1	0.9	0.6	0.6
Total	**40**	**36**	**32.8**	**27**	**31.6**

The four designs were compared against the five criteria. Each criteria was given a value of importance ranging from 1-10, with 10 being highest importance. Each design was ranked from 0-1 and multiplied by the criterias ranked value. The values in the bottom row were each compared to the maximum criteria value (40). The highest scoring design was selected. CAD illustrations for the the key slot and single-piece shaft designs are shown in Figure 2a and 2b.

The final design evaluation resulted in the selection of the single-piece shaft. It was determined that this design could be made in-house from a 3" diameter, $3\frac{3}{4}$" length raw stock of 6061-T6 aluminum. This design scored the highest in the matrix design criteria and was selected to move forward for prototyping.

(a) Impeller with Shaft and Key Slot

(b) Impeller with Single-Piece Shaft

Figure 2: Impeller Designs

7.2 Motor Selection

This concept scoring method was also used when evaluating purchase of the motor. Criteria including torque, power, weight, and price were used when comparing motor specifications. Our final decision resulted in the selection of a TP Power Brushless 4070 CM Series Motor which has a common application in RC fast electric boating.

7.3 Pump Housing

Upon reviewing an earlier design, the customer requested the addition of an axial thrust bearing along the shaft of the pump. This addition is intended to stabilize the rotating element, as well as absorb the axial forces induced on the pump. The addition of this component to the design resulted in the addition of a shaft collar to retain the bearing. It also required the design of another housing component between the shaft coupler and main pump housing. This added housing plate was designed to retain the rotating elements from being able to shift inward toward the motor under pressure. This design is shown in Figure 1.

8 Progress on Design

After defining the qualitative criteria and selecting a design to pursue for the impeller, motor, and pump housing, we began to define the quantitative criteria.

8.1 Impeller Design

With the decision for combining the impeller and shaft concluded, the impeller could now be dimensioned. Outer diameter, eye diameter, and pump housing diameter were derived from the mass flow rate and pressure requirements provided by PSAS. The design specifications determined from these analyses are found in Table 6. The calculations for these specifications can be found in Appendix A.

Table 6: Engineering Criterion for Impeller Characteristics

Parameter	Units	Value
Mass Flow Rate	[kg/s]	0.93
Impeller Tip Speed	[ft/s]	211.32
Pressure Gain	[psi]	343
Impeller Diameter	[in]	2.682
Eye Diameter	[in]	0.267
Housing Diameter	[in]	3.091

8.2 Motor Selection

It was determined that the motor needed to provide a minimum power output of 2.053 kW and 0.88 $N \cdot m$ of torque. The calculations for these parameters can be found in Appendix A. The TP Power Brushless 4070 CM Series Motor was selected and purchased. This motor provides a maximum of 5 kW of power with a delivery of up to 200 A of current. A primary reason for the selection of this motor was its rotation rate capabilities. During tests performed to study the motor's performance, speeds over $50,000$ rpm (unloaded) were observed.

8.3 Pump Housing

A pump housing prototype was machined out of plastic (UHMW). This was used to provide a better understanding of machining operations and overall fit before machining the aluminum prototype. This also proved beneficial to tooling life and cost reduction, as UHMW material is easy to machine with minimum wear on cutting tools. Bore and depth dimensions as well as pipe thread type needed for the pipe to front housing case were finalized based on length of thread engagement calculations done during out internal search. An accurate analysis for the minimum thread engagement length resulted in a reduced overall thickness of the front housing case. The benefits of this analyses were more flexible tool cutting selection, faster machining time and weight reduction for the main housing case.

9 Conclusion

The key milestones met this term were finalizing the designs for the impeller, motor, and pump housing. By pursuing a Barske impeller and a single-piece shaft connection, the low flow, high pressure objective should be met while allowing for manufacturability in-house. Reducing the sections of pump housing from five thick sections down to three smaller pieces will help achieve the weight reduction requirements.

Although we are still far from completion, the rate at which we have been able to machine components for prototyping and testing has moved rapidly. We have been able to verify tool paths by machining plastic iterations of nearly all of the pump housing components. Additionally, several impeller designs made of aluminum have already been completed.

The current state of the project is close to our target milestones. Working closely with our sponsor, we have been able to communicate weekly on progress and have met all customer needs thus far. Key milestones we expect to cross next term are the completion of the aluminum pump housing. This will allow for final assembly and testing of the IPA pump. We also expect to finalize our control systems and material selection for the pump components to be used with the LOX pump.

The schedule anticipated by PSAS has been exceeded by having prototypes in earlier than expected. Our team has shown tremendous effort in the way of producing CAD design and machining parts. However, we are aware that performance capabilities will not be identified until testing has been completed. This testing will begin as early as the first week of April. The pumps design will only be verified once it has been tested during a full operation cycle.

Appendices

A Design Calculations

The following calculations were performed to determine the optimized impeller dimensions for the Electric Feed System pumps. The process for liquid oxygen is shown.
Given:

$$m_{mix} = 1.8 \qquad \Delta P = 343\ psi$$
$$f = 2200\ N \qquad U_{ss} = 7000$$
$$I_{sp} = 242.4\ s \qquad \eta = 60\%$$
$$P_i = 40\ psi \qquad L = 0.3$$
$$P_L = 53\ psi$$

Find:
Impeller dimensions and motor requirements for liquid oxygen pump.
Solution:
A mixture ratio of $m_{mix} = 1.8$ was provided by the customer. This value is the ratio of liquid oxygen to isopropyl alcohol. Additionally, a thrust of $f = 2200\ N$ and specific impulse of $I_{sp} = 242.4\ s$ were provided. The mass flow rates are then found as:

$$\begin{aligned}\dot{m}_{tot} &= \frac{f}{g \cdot I_{sp}} \\ &= \frac{2200\ N}{(9.81/m/s)(242.4\ s)} \\ &= 0.93\ kg/s\end{aligned}$$

$$\begin{aligned}\dot{m}_{LOX} &= \frac{\dot{m}_{tot}}{1 + (1/m_{mix})} \\ &= \frac{0.93\ kg/s}{1 = 1/1.8} \\ &= 0.59\ kg/s \\ &= 1.31\ lbm/s\end{aligned}$$

The required head rise, H_p, inlet head, H_i, and vapor pressure head, H_v, are found as [1]:

$$\begin{aligned} H_p &= 144 \times \frac{\Delta P}{\rho_{LOX}} \\ &= (144)\frac{343\ psi}{71.230\ lb/ft^3} \\ &= 693.41\ ft \end{aligned}$$

$$\begin{aligned} H_i &= \frac{P_i}{(\frac{\rho_{LOX}}{\rho_{H_2O}}) \cdot 0.433} \cdot \frac{1}{2} \\ &= \frac{40\ psi}{(\frac{71.230\ lb/ft^3}{62.428\ lb/ft^3}) \cdot 0.433} \cdot \frac{1}{2} \\ &= 40.48\ ft \end{aligned}$$

$$\begin{aligned} H_v &= \frac{(0.000145038)(144)P_{v,LOX}}{\rho_{LOX}} \\ &= \frac{(0.000145038)(144)(2.346\ psi)}{71.230\ lb/ft^3} \\ &= 2.35\ ft \end{aligned}$$

The impeller tip speed, u_t, is found by [1]:

$$\begin{aligned} &= \sqrt{2gH_p} \\ &= \sqrt{(2)(32.2\ ft^2/s)(693.41)} \\ &= 211.32\ ft/s \end{aligned}$$

The available NPSH and rotational NPSH for the pump are found as [1]:

$$\begin{aligned} NPSH_a &= H_i - H_v \\ &= (40.48 - 2.35)\ ft = 38.14\ ft \\ NPSH_r &= \frac{NPSH_a}{\tau} \\ &= \frac{38.14\ ft}{2} \end{aligned}$$

Here, τ is the Thoma Parameter. The rotational speed and pump specific speed are [1]:

$$\begin{aligned} n &= \frac{U_{ss} NPSH_r^{0.75}}{21.2\sqrt{Q}} \\ &= \frac{(7000)(19.07)^{0.75}}{(21.2)\sqrt{\frac{1.31\ lbm/s}{71.230\ lb/ft^3}}} \\ &= 22206.87\ rpm \end{aligned}$$

$$\begin{aligned} n_s &= \frac{(21.2) n \sqrt{Q}}{H_p^{0.75}} \\ &= \frac{(21.2)(22206.87\ rpm)\sqrt{\frac{1.31\ lbm/s}{71.230\ lb/ft^3}}}{(693.41\ ft)^{0.75}} \\ &= 4513.91\ rpm \end{aligned}$$

Now the impeller and motor values can be found. The impeller diameter, D_o, eye diameter, D_i, and impeller housing diameter, D_p, are [1]:

$$\begin{aligned} D_o &= (12)\frac{u_t}{2n_s} \\ &\boxed{= 2.682\ in} \end{aligned}$$

$$\begin{aligned} D_i &= (12)\left(\frac{4Q}{\pi \phi n_{rad}(1 - L^2)}\right)^{1/3} \\ &\boxed{= 0.267\ in} \end{aligned}$$

$$\begin{aligned} D_p &= (1.152) D_o \\ &\boxed{= 3.091\ in} \end{aligned}$$

Where ϕ is the inducer inlet flow coefficient. Because an inducer is not being used, $\phi = 1$. Note that the rotational speed used to calculate D_i is in radians. The power and torque requirements of the motor can now be identified [1]:

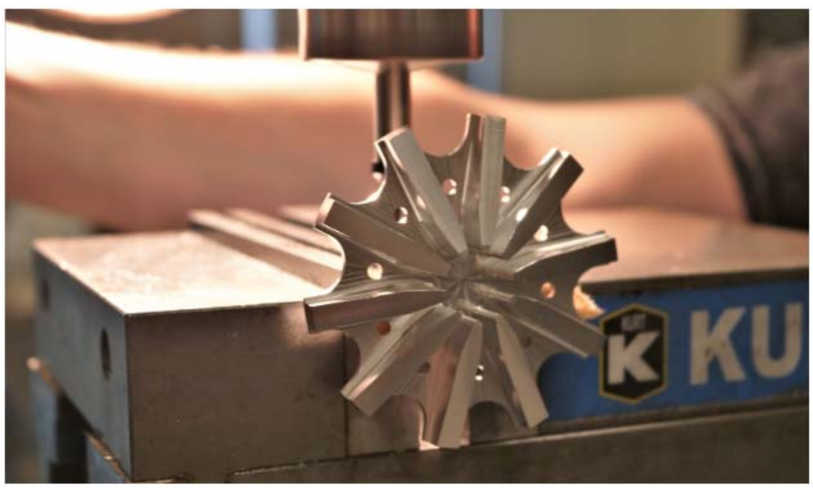
$$
\begin{aligned}
P &= \frac{\dot{m}H_p}{(0.738)\eta} \cdot \frac{1}{1000} \\
&= \frac{(1.31\ lbm/s)(693.41\ ft)}{(0.738)(0.60)} \cdot \frac{1}{1000} \\
&\boxed{= 2.053\ kW}
\end{aligned}
$$

$$
\begin{aligned}
T &= \frac{(9.5488)P}{n} \cdot 1000 \\
&= \frac{(9.5488)(2.053\ W}{2220687 rpm} \cdot 1000 \\
&\boxed{0.88\ N \cdot m}
\end{aligned}
$$

B Additional Figures

(a) Turned Shaft with Faced Impeller Stock

(b) Machined Impeller Vanes



(c) Balanced Impeller

Figure 3: Impeller Machining Processes

C References

[1] I. Karassik, 2007,"Pump Handbook" ($4^{th}Ed$)

[2] E. Oberg, 2012,"Machinery's Handbook" ($29^{th}Ed$)