Cost Effective High Accuracy Model Positioning

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Within the field of aerospace engineering, the ability to simulate and validate flow fields around a scale model is crucial. This is generally accomplished through the use of low speed wind tunnels to allow the user to observe flow fields and measure various loads on a test specimen. To augment the aerodynamic testing capabilities of a wind tunnel, an automated or manual model positioning system (MPS) is needed in order to accurately orient test articles with respect to the airflow. Most commercial off the shelf (COTS) MPS cost around $300,000 for 2 degrees of freedom (DoF), mainly pitch and yaw. The goal of this project is to design a cost effective, custom-built system with 4 DoF in pitch, plunge, yaw, and roll. The MPS is designed to provide +/-30° in pitch with an accuracy of +/-0.1°, +/-10 cm in plunge with and accuracy of +/-0.5 mm, +/-30° in yaw with an accuracy of +/-0.1°, and finally +/-45° in roll with an accuracy of +/-0.5°. The MPS shall be capable of automated and manual control over a local area network (LAN) via a LabVIEW virtual interface. Successful demonstration of required ranges and accuracies shall prove functionality of the MPS and allow for future use inside the specified wind tunnel.

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I. Introduction

In aerodynamic research, orientation of a model is critical. The orientation of a body greatly affects the flow around it. The model positioning system (MPS) shall provide precise positioning of research models in the University of Colorado at Boulder's new wind tunnel. The MPS will be installed in one of three test sections in the wind tunnel. The wind tunnel and close up of the full test section are shown in Figure 1.

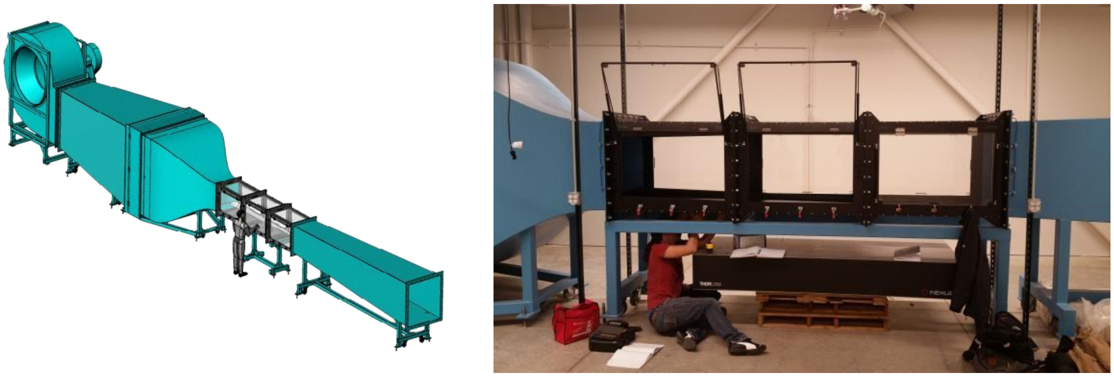

Figure 1. Wind Tunnel and Full Test Section. *On the left is the Solid Works model of the wind tunnel with engineer to scale. On the right is the actual tunnel test section being installed.*

The three test sections are each 1 meter long by 0.76 meters high and 0.76 meters in width. The specific needs the system shall fulfill are the need for a highly accurate, easy to use, and cost effective alternative to what is currently on the market. The accuracy need comes from the design requirements presented to the team from the customer. The customer wants a highly accurate platform for experimental aerodynamic that will be performed in the new wind tunnel. The easy to use component comes from the future users of the system. In the future, users will be graduate students and new professors so an easy to use product will help reduce the work load with a system that has little learning curve. The final need for the MPS is it must be a cost effective alternative to systems offered by companies that specialize in quality systems. Extensive research performed by the team has found the cost for a custom model positioning system can range from $100,000 to $450,000 depending on the project requirements. A few of the companies researched for this data were Aerolab[1] and Aerofms[2]. These companies also quoted lead times from 9 months to 18 months. The MPS designed by the team shall be built and tested within an $8,000 budget over the course of two school semesters. The budget total came from two sources, $5,000 comes from the customer and $3,000 came from a grant, which the team was awarded by a financing committee at the University of Colorado. The cost for a system from Aerolab or Aerofms includes the cost of labor while the $8000 for the universities MPS will not include labor. These three needs present the design team with a few challenging issues that will be addressed in detail later in the Design Objectives. Challenges in designing the MPS include accurate communication between all subsystems, precision machining, and sticking to a tight budget and schedule. The following sections will cover how the team has worked around design challenges to provide a successful system starting with design objectives and levels of success. Following this section, the methodology section will cover how these requirements were satisfied in the design of the final system and finally the design results will be presented to display how the system performed based on specifications given by the customer.

II. Design Objectives

The main requirement for the MPS is to verify/validate the requested ranges in pitch, yaw, roll, and plunge as well as verify/validate the ranges within the requested accuracy of all DoF.

Table 1. Levels of Success

	DoF	Range	Position/Angular Accuracy	Validation Expectations
Level 1	Pitch Yaw	Pitch = ± 30° Yaw = ± 30°	Pitch = ± 0.1° Yaw = ± 0.1°	Basic verification of movement
Level 2	“ “ Roll	“ “ Roll = ± 45°	“ “ Roll = ± 0.5°	VICON w/o static load
Level 3	“ “ Plunge	“ “ Plunge = ± 10 cm	“ “ Plunge = ± 5 mm	VICON w/ static load
Level 4	“ “	“ “	“ “	In tunnel w/ aerodynamic load

The levels of success for the MPS are described in **Table 1.** The table is split up by degree of freedom, range and accuracy of the degree of freedom, and validation expectation for the MPS. For aerodynamic testing, the most important degrees of freedom to test a model in are pitch and yaw; therefore, for level one success both of these degrees of freedom shall be validated and verified. Plunge is described as moving the system vertically up and down and when validated and verified shall complete the highest level of success in DoF, range and accuracy. Throughout the testing phase of the MPS, validation will be essential to verifying the feasibly of the system. Level 1 success is basic verification of the system; meaning, testing the system though rudimentary methods discussed in Design Results. The next two levels of success involve using a system of cameras to achieve precise positions to be compared with input commands. The difference between level 2 success and level 3 is determined by whether or not the system is tested with static loading or not. The final level of success involves testing within the designed environment, the wind tunnel. Again this will be discussed in more detail in Design Results.

The main functional requirement (FR) of the MPS is to positional a model. The first design requirement (DR) derived from the FR is the system shall have four DoF in pitch, plunge, roll, and yaw. The second DR defines the ranges and accuracies described in **Table 1.** The purpose of these ranges is to simulate the possible conditions an airfoil could experience. The purpose of these accuracies is to have an understanding of how accurate the MPS has the ability to position/hold the position of a model for validation of future research in the wind tunnel. The final DR states the system shall have a zero reference point. This is important for calibration when the system is inserted in the wind tunnel as well as feedback from a few incremental encoders which are used for use feedback.

The critical project elements (CPE) for the MPS, which are most relevant to the topic of this paper, involve testing. This means the system requirements must first be verified outside of the wind tunnel followed by the validation of the verified requirements inside of the wind tunnel. Testing outside of the wind tunnel is important for multiple reasons. The first reason is to troubleshoot whether the system has the ability to reach the requested ranges and accuracies and debug the system to get it working properly. The next reason is if anything breaks or does not work as expected then the wind tunnel would not be damaged through the initial testing process. The next CPE is testing within the wind tunnel. This is important because this test validates the requested requirements within the environment the MPS was designed for.

III. Design Methodology

The overall design of the MPS followed directly from the design requirements laid out by the customer. There were many design requirements, but the ones which had the largest impact on the overall design were the pointing accuracy requirements, the physical interface requirements, and the software/electrical interface requirements. These three areas were what determined the overall shape of the system, as well as the components it is comprised of. Each requirement area and its impact on the development of the system are outlined throughout Design Methodology.

The first major driver of the MPS design was the pointing requirements put in place by the customer. As previously mentioned, the system is tasked with positioning a model in four degrees of freedom with accuracies as small as 0.1^{O} (in pitch and yaw). This pointing accuracy must also be able to be met under torques as great as 65 Newton-meters for yaw and 175 pounds of lift force for pitch and plunge. As such, the team needed to select components that allowed for very small increments in rotation while under significant sustained loading. This meant the motors driving the pitch and yaw mechanisms needed to be controlled to high resolutions of less than 0.1^{O}, and significantly high torque and lift force values. Through research, the team found that most brushless DC servo motors available on the market, and within the budget, did not have sufficient resolution. What this meant for the yaw mechanism was the implementation of a gear. This gear, shown in Figure 1, would allow for the motor driving the yaw mechanism to achieve a control resolution less than the needed requirement as well as hold greater loads experienced within the wind tunnel. With the purchase of a Teknic CPM-MCPV motor, the final design, with the implementation of a worm gear with a ratio of 40:1, will be able to achieve resolutions of roughly 0.01^{O} under load. This is almost ten times greater than that of the design requirement. The gear also allows the motor to hold torques of 128 Newton-meter, roughly three times greater than needed.

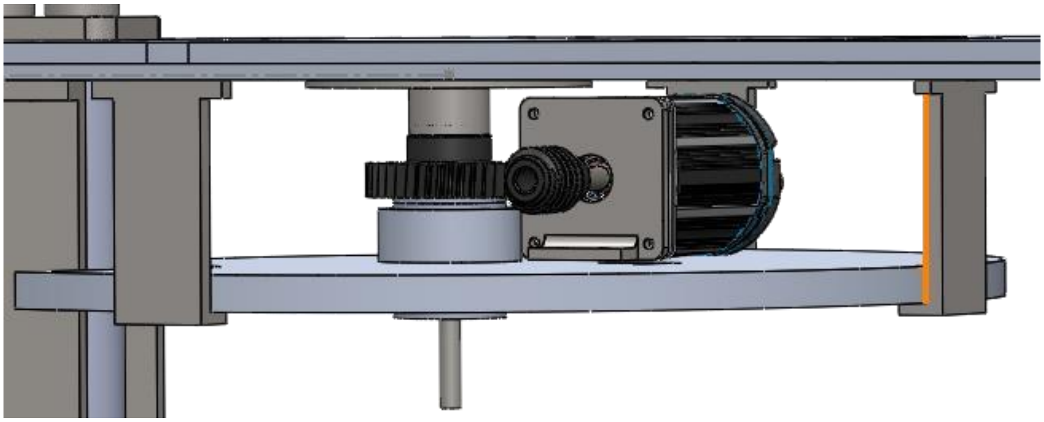

Figure 1. Design of Yaw Subsystem with Gear created in Solid Works.

The choice for linear actuators to control pitch and plunge stemmed from problems trying to design a crescent sting arm and the desire to simplify the plunge mechanism. The initial design looked very similar to a system by Aero FMS shown in Figure 2.

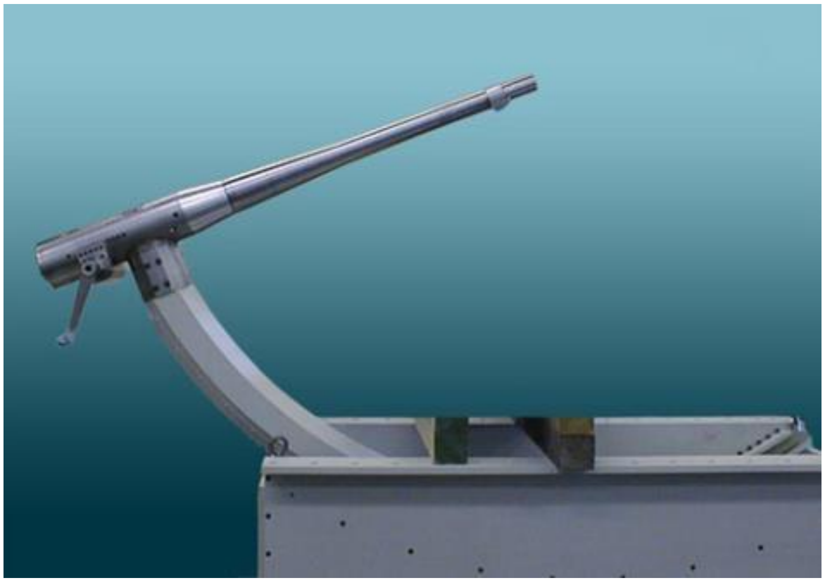

Figure 2. AeroFMS Crescent Sting.

The crescent sting arm system was changed to the current dual actuator system after a few problems were discovered. Some of the problems included the colocation of the yaw and pitch axis along with an opening in the test section which was required so that the system can move in all the ranges defined in the levels of success. One specific company, which had multiple dual, struts systems for pitch was Aerolab. One of the designs can be seen here in Figure 3.

Figure 3. Aerolab Dual Strut MPS.

This system has a rotary motor that adjusts the pitch of the model by a series of struts. The only problem with this system compared to the requirements is plunge. To achieve plunge this entire system would have to move up and down. This would require a very strong expensive motor, which the team did not have the budget. This plunge idea would also require a very large support system, which would create a demand for strong and expensive material. To solve this problem, the team decided on using linear actuators. Linear actuators provide both pitch and plunge simultaneously. The only challenge that comes with this decision is finding linear actuators, which provide a high enough, force with a long enough stroke length. Through extensive research the team found actuators from Progressive Automations[3].The actuators chosen from this company were their PA-03 models, which have a customizable stroke length up to 40 inches and can withstand a continuous force of 600 pounds. 600 pounds well exceeds the expected lift force of 175 pounds, which was estimated from a NACA 0012 airfoil with a 0.5 meter span and 0.1 meter chord at an angle of attack of 30 degrees.

In summary for the pitch mechanism, the idea of using a rotary motor like the yaw mechanism was abandoned altogether. Instead the team decided to implement two linear actuators. As discussed previously this was mainly so that the system could achieve both pitch and plunge. Using the differential stoke length between the two actuators, accuracies of 0.1_{o} in pitch can be met. The linear actuators are also able to hold loads of up to 600 pounds, eliminating the worry of pointing accuracy being affected by loading in pitch.

Materials to use dictated another way in which the pointing accuracy requirements affected the design of the MPS. The loading the system would experience in the wind tunnel drove the team to use materials that would hold their shape and not deform during a test (forces of around 40 lbs. expected). The MPS needed to be as lightweight as possible for ease of movement, but it also needed to have strength so that it would not buckle or break during a test. As a result, most of the system is made of aluminum. This allows the system to be more lightweight than it would be if it were made from steel, but still allows the system to have enough strength to hold the loads it is expected to experience.

The next major design driver was the requirement based upon the physical integration of the MPS with the wind tunnel. These requirements had a large impact on the overall geometry of the system. To begin, the MPS needed to interface within the wind tunnel. This meant the manufacturing of a custom base plate that would allow the pitch and yaw mechanisms to be securely mounted within the wind tunnel. The geometric constraints of the wind tunnel also limited the geometry of the linear subsystem. The linear actuators had to both fit under the test section itself, and they also were constrained within the test section. In other words, the linear actuators could only extend so far before they came into contact with the test section itself. As a requirement, the MPS was not allowed to come into contact with the test section, and therefore this determined the overall stroke lengths of the linear actuators. The final stroke length of the linear actuators was 34 inches. This allowed for the requirement in range of ±30^{O} to be met, while not coming into contact with the test section itself.

Figure 4. MPS shown within test section.

Along with the physical integration, the electrical integration of the system with the wind tunnel had a large impact upon the final design. The main design requirement was that the system needed to interface with a CompactDAQ chassis from National Instruments (NI). In turn this meant the main data acquisition used within the MPS needed to come in the form of DAQ modules from Native Instruments. This led to the purchase of two DAQ modules, the NI 9401 and the NI 9361. These two modules allow input from incremental encoders that read back the positions of the yaw motor as well as the linear actuators. Another requirement that shaped the design of the system was that it must use LabVIEW as an interface. This is also partially what decided the purchase of the NI DAQ modules. All of the software within the MPS is written to run through LabVIEW.

IV. Design Results

With the design methodology above in mind, the final design of the system was decided upon. The final system consists of four main sub systems: Base plate, yaw, pitch/plunge, and roll.

The design of the base plate used in the MPS was taken almost completely from the design of the base plate currently being used within the wind tunnel. The main difference between the two is that the MPS base plate has a slightly larger yaw plate than the current plate. This subsystem's main purpose is to allow the system to physically mount within the wind tunnel section.

The yaw subsystem mentioned previously is combined of the yaw plate, the worm gear, and the Teknic CPM-MCPV motor. This subsystem verifies the requirement for the MPS to position a test article in the test section within a range of ±30^{O} with an accuracy of ±0.1^{O} in yaw. The Teknic motor is controlled by LabVIEW through the NI 9401 DAQ. In reality, the system can position the test article with an accuracy of ±0.01^{O}, and can sustain torque loads of up to 120 N-m thanks to the gear implemented within the system.

Figure 5. Final Design of MPS.

The pitch and plunge subsystem is comprised of two PA-03 linear actuators. This subsystem verifies the requirement for the MPS to position a test article in the test section within a range of ±30^{O} with an accuracy of ±0.1^{O} in pitch, as well as within a range of ±10 cm with an accuracy of ±0.5 mm in plunge. The two PA-03 linear actuators are rated for 600 pounds of force, and are controlled by LabVIEW through the NI 9304 DAQ.

The final subsystem responsible for positioning the test article, that being roll is somewhat different from the other two. It is different in that roll is the only stationary subsystem (other than the base plate). The roll subsystem is comprised of the sting and the sting cap. The subsystem allows a user to manually set the roll of the test article before testing begins. Once the test has started, the roll cannot be adjusted until the test has concluded. The roll subsystem allows for the MPS to position a test article within a range of ±45° with an accuracy of ±0.5°. As the system is completely stationary, there are no motors involved, and therefore roll is not controlled by LabVIEW.

There are many separate components that make up the system; some of which were bought, and some of which were machined in house. The table below documents which items were procured and which were and which were machined.

Table 2. Procured and Manufactured Components

Procured	Manufactured
PA-03 Linear Actuators x2	Base Plate
Worm Gear	Yaw Plate
NI 9301	Sting Side Piece x2
NI 9304	Sting Face
Aluminum for Base Plate and Yaw Plate	Sting Cap
Incremental Encoders x3	Sting 3rd Arm x2
PCB Board	Linear Brackets
PCB Components	Yaw Brackets
500 lb. Hydraulic Lift Cart	Linear Collars
Bearings	Yaw Shaft Flange
Metal Rod x3	Linear Bearing Mount
Gear Plate Bracket	Sting
Teknic CPM-MCPV and Power Supply	Yaw Shaft
	Worm Gear Edit
	Gear Base
	Actuator Mount
	Yaw Spacer

Currently, all components listed in the table above have been received from suppliers or their machining has been completed. The next step in the process was to ensure that every component agreed with the final design. This means that each component needed to be tested for general functionality before the subsystems could be assembled. Most of the components that were procured needed to be checked against their specification sheets in order to determine that they would work as designed. These components were mainly electronic in nature, like the Teknic motor or the incremental encoders. Other procured components were easier to test for general functionality, because they simply needed to be the right size, like the bearings. The machined components on the other hand had no spec sheets to compare to. Their functionality testing was simple, as they only needed to be measured in order to ensure that they were the same dimensions as their CAD counterparts. All component general functionality was verified, with no defective equipment.

Currently the yaw subsystem and the linear subsystem are being assembled for initial testing. This testing consists mostly of communication between the subsystems and LabVIEW. The goal is to verify that LabVIEW can successfully communicate with and control each subsystem. From there, the testing will move to verifying the pointing accuracies of each subsystem. Using LabVIEW, the MPS will be sent a position in either: pitch, plunge or yaw. From there, the team will measure the position that the system moved to, and will reference that to what it was commanded. Through many tests, each subsystem will be calibrated so that it will reach the right position with the needed accuracy each time it moves.

V. Conclusion

The system is currently undergoing full scale integration and testing to valid high levels of success through the use of methods described previously. The control of the system is the biggest remaining task to achieve the higher levels of success. Once completed the system will be handed over to the design team's customer. At that point all of the specific needs of the system will be fulfilled as described in this paper which were: highly accurate, easy to use and cost effective. The MPS will provide an accurate platform that will be able to accurately position a model for aerodynamic research at the University of Colorado. This will allow the university to make significant leaps in understanding advanced aerodynamics. The design team has currently used about $7000 of its $8000 budget

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