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Preliminary Design of a Magnetic Measurement System for the Detector and Production Solenoids of the Mu2e Experiment

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I. Introduction

The Mu2e experiment looks to observe the conversion of muons to elections in an attempt to discover evidence of massive, beyond the standard model, particles. To achieve this, subatomic particles will pass through three solenoids, each with a different function. In the production solenoid (PS), bunches of protons accelerated to 8 GeV from the booster ring will strike a fixed target. This collision will produce pions that then decay into muons. In the upstream end of the transport solenoid (TS), negatively charged particles drift up, and an offset collimator makes a sign and energy selection. These drift back to the center in the downstream end of the TS, and enter the DS where some of the muons are stopped in a thin target. In the DS, an electromagnetic calorimeter and a magnetic spectrometer will take the necessary measurements to look for electrons with precisely the muon mass (105 MeV).

The integrity of the data relies on knowing what the magnetic field looks like with a fair degree of accuracy. Engineers are designing the solenoids to produce a complex magnetic field devised for the experiment; however, once these solenoids are produced and switched on, the magnetic field will need to be manually measured to ensure that the specifications are indeed met. To that end, the experiment requires either one or multiple systems capable of mapping the magnetic field of the production and detector solenoids. For a number of reasons, it will not be practical to measure the TS directly; therefore, an indirect approach of tracking an electron source will be used instead to validate the transport channel properties.

II. Problem Statement

The magnetic field requirements of the Mu2e solenoids were laid out early in 2012 (mu2e docdb 1275). These requirements form the basis for the magnetic measurement system. Note that detailed functional and technical requirement specifications are still being developed. That document outlines the radial and axial dimensions out to which the magnetic field must be measured. This results in a volume of 0.7m radially and 9.1m axially for the detector solenoid; and a volume of 0.25m radially and 4m axially for the production solenoid. In addition to these volumes, it is required that both systems be capable of measuring the first meter of the transport solenoid on either side out to a radius of 0.15m and possibly for some distance (~0.5-1m) at the non-TS ends of the PS and DS. In both cases, the first meter of the TS is straight and the data gathered there will provide additional insight into how the magnetic fields of the three solenoids interact.

The other requirement of these systems pertains to the method by which the magnetic measurement system enters the solenoid. For the detector solenoid, the system should ride on precision rails that will be installed one meter apart on the interior of the cryostat. For the production solenoid, the system should ride on precision rails that will be placed outside the solenoid, while the measuring components should be mounted on a cantilevered beam that extends into the solenoid.

One last requirement lies in the precise placement of the probes within the solenoids. The exact precision has not yet been determined; however, the probes will likely need to be placed with a precision on the order of 100 micron. To achieve this, the position of the carriage on the rails, the angular position of the rotating arms, and the position of the central axle with respect to the center of the magnetic field will need to be adjustable to ensure perfect initial placement of the probes and to minimize error in positioning throughout the measurement cycle.

III. Previous Systems

Mapping a magnetic field is not a new idea. Similar situations have arisen in many other high-energy physics experiments across the globe, a few of which are described below.

1. CDF

When the Collider Detector at Fermilab (CDF) was first commissioned, a similar study was performed to understand the magnetic field inside the solenoid. In this case, rails could not be mounted inside the magnet bore. To overcome this, the engineers designed the carriage to ride on rails outside the detector (Figure 1). The measurements were taken with a single propeller at the end of a cantilever. This propeller had one fixed NMR probe at the center and another sensor on a shuttle that moved to certain positions along the propeller. The propeller rotated much the same as the CMS design to move the sensor into various positions. Of particular concern in this design was Eddy currents. This is the resistive force felt by conductive objects (i.e. metals) in a magnetic field. This force impedes motion, increasing the power necessary to propel the system. To address this, most of the components that entered the magnetic field were manufactured from carbon-fiber composites.

2. CMS

The Compact Muon Solenoid (CMS) at CERN is one of two general-purpose detectors attached to the LHC. It is also the only experiment in which Fermilab is directly involved. When CMS was first being commissioned, engineers at Fermilab created a magnetic measurement system which consisted of a stainless steel and fiberglass carriage riding on stainless steel rails (Figure 2). Atop this carriage was a rotary vane pneumatic actuator whose power was transmitted through a gear system to a central axis, on which there were two propellers. At the bottom of the carriage, a separate pneumatic motor and gear train engaged a Kevlar toothed belt to move the carriage along the bore. Each of the propellers was fitted with four Hall probes and one NMR probe to take magnetic measurements. The propellers rotated in 7.5 degree intervals and the carriage moved in steps of 5 cm.

3. ATLAS

A Toroidal LHC Apparatus (ATLAS) is the other general-purpose detector attached to the LHC. The system consists of a metallic bar that runs along two rails that are mounted on each side of the cylinder, half way up (Figure 3). Attached to this bar are four propellers at 90 degree intervals, each with 12 magnetic measuring sensors and 1 NMR probe. Documentation for this design reveals that a fair amount of thought went into minimizing weight and magnetic components. This research informs part of this design process as it is necessary to minimize the same quantities for this system.

IV. Detector Solenoid Design

During the Department of Energy CD1 Review of the Mu2e project, rough designs were outlined for the two magnetic measuring systems. The concept for the DS mapping system is based upon the CMS system; however, it incorporates an additional, smaller propeller one meter in front of and parallel to, the front main propeller, as well as a counterweight attached to the central axle on the opposite side of the rear main propeller (Figure 4). This smaller, cantilevered propeller is to be used to take measurements of the first meter of the TS, into the straight collimator, as well as close to the axis all along the DS independently of the large-radius propeller probes. The counterweight ensures that the system is not unbalanced.

1. Carriage

The carriage is built from the ground up. It is supported by four linear motion carriages that attach to precision rails. These linear motion carriages are connected by four square tubes. The first two tubes each connect two linear motion carriages across the rails, while the second two tubes connect the first two tubes together along the rails. This forms a square bracket. On top of this square bracket sits a platform where the carriage drive system is located. Moving upward, four more square tubes are placed vertically in the corners of the square bracket. Two final square tubes are attached in the front and back of the carriage at the top of the vertical tubes, each connecting two of the vertical square tubes. On top of these two horizontal tubes is another platform. This platform will carry the propeller drive system. Four panels will surround the carriage, each attached to two of the vertical tubes. These panels will provide additional rigidity in the carriage. All of these basic design elements are shown in a CAD model in Figure 5.

2. Propellers

This design calls for two types of propellers. The first will be a large propeller and will reach a maximum radius of 0.7m while the other is intended for use in the TS and will only reach a maximum radius of 0.15m.

Large Propellers

These propellers will be made from two lengths of tubing and two fiberglass panels. The two fiberglass panels will be cut to a trapezoidal shape. A keyed hole that corresponds to the shaft will be drilled into each panel. The two panels will be attached to lengths of tubing as shown in Figure 6. The position of the keyed hole and the dimensions of the trapezoidal panels are determined by the 0.7m radius requirement that defines the distance from the center of the keyed hole to the smallest edge of the panel and an internal requirement that requires the center of the keyed hole to be concurrent with the center of gravity of the panel. There will be two of this type of propeller produced: one for the front of the carriage and one for the rear. This redundancy will allow the rear propeller to check the measurements of the front propeller.

The two panels for the front propeller will have a keyed hole that will be diametrically opposite to the keyed hole in the two panels for the rear propeller. This will ensure that the two propellers are offset angularly by 180 degrees. Additionally, the design calls for the two propellers to be axially offset such that the sensors will be 700mm from each other. This number is arbitrary; however, a round number makes it easier to ensure the rear propeller is taking data in an easily achievable position previously occupied by the front propeller. The specific number is dictated by the length of the carriage.

Small Propeller

This propeller will be made in the same fashion as the large propellers with only the size changing to accommodate the smaller radius of the TS. Also, to ensure the stability of the system, a counterweight will be attached to the end of the shaft opposite the small propeller to balance the weight of the small propeller. The weight of the counterweight will be determined by the final size, weight, and position of the small propeller.

3. Carriage Drive System

The carriage is to be driven by a continuous, reversible air motor. This motor will drive a gear system containing four gears that reduce the speed and increase the torque by a factor of six. The gear ratio of the system at present is arbitrary and may need to be adjusted as the precision requirements evolve. In any case, the final gear of the system will transmit the power to a toothed pulley wheel via two sprockets and a chain. The chain will make use of a chain tensioner (not shown in the CAD model) to ensure proper power transmission. The toothed pulley wheel will engage a timing belt that will run along the bottom of the cryostat. As the pulley wheel turns, it will move the carriage along the timing belt and down the bore. This system is shown in Figure 7.

The motion of the carriage along the rails will be controlled by a computer control system that will control the air flow into the motor and will adjust the position based on user commands and with respect to the feedback from a linear motion encoder. The advantage of using an encoder is freedom with regard to step size. In previous systems, the motion was prescribed by a set number of rotations of the motor, which limited the motion to one fixed step size. By using a linear encoder, the step size can theoretically be altered to be larger in areas of uniform magnetic field, then decreased to provide a finer data set in areas of a large magnetic field gradient.

4. Propeller Drive System

The propellers will be driven by a system similar to the one describe above. The final gear in the gear system will be on the central axle, where the motion of that axle will turn the propellers. This can be seen in Figure 8. The motor will be controlled by a similar control system which will instead respond to feedback from an angular encoder attached to the central axle.

5. Cable Management

The system will have a number of cables running from the sensors and tubes running from the motors to a location outside the solenoid. To ensure the cables and tubes do not interfere with the motion of the propellers nor get tangled or kinked, they will be routed to the outside using a cable carrier. Cable carriers resemble a mix between a snake and a chain. They form a protective case that keeps all of the cables together and weighs them down to stay on the floor of the cryostat, away from the propellers.

6. Other Design Ideas

Though this design idea seems to have the most merit in terms of previous use and success, there are a couple other ideas that may prove useful if a new design is necessary.

One Disk

This design seems most likely to be implemented if there are a sufficient number of sensors available to take magnetic measurements. The main reason why propellers are used is to maximize the use of a small number of sensors. By using propellers, a few sensors can be swept around the entire circle, taking all of the necessary data. If the budget allows for more sensors, it might be possible to spread them over a large disk, taking all of the data in a plane at once. This would eliminate the need for rotation, which in turn would decrease the complexity of and possible error in the measurements.

Circular Carriage

Another idea centers on building a cylindrical carriage the size of the bore. Such a carriage would have wheels mounted along the circumference to allow the apparatus to roll down the bore. Either propellers or the one disk idea could be used to take the measurements. The main advantage to this idea is the elimination of the rails, for reasons described in the "Sources of Error" section below.

V. Production Solenoid Design

The design of a magnetic measuring system for the PS grew out of the design for the DS. As such, it retains many of the design elements previously discussed. The full design can be seen in Figure 9. The following are the changes made to the DS design such that the system will work for the PS.

1. Frame

For reasons discussed below, the frame height needed to be increased. To that end, the PS design incorporates vertical square tubes of twice the height to allow for a third tier of horizontal square tubes (Figure 10). This third tier is then used to mount exterior plates twice the size of that of the DS design. This additional area above the axle allows for tensioned cables to be attached to the end of the axle system to correct for the bending of the cantilevered arm.

2. Axle

The axle necessarily must be longer to accommodate the requirement that the system not be physically attached to the PS. This introduces the two problems of the inaccuracies introduced by the axle bending as well as the difficulty of rotating a bent axle. To compensate for both problems, a c-channel will be mounted under the axle with ball bearings mounted along the c-channel to keep the axle in position. This c-channel will then be attached to the frame with tensioned cables as described above.

3. Propellers

For this design, the number of propellers must be kept at a minimum. This is because as more propellers are introduced, the amount of axle that can be kept straight and level is reduced. With this in mind, the PS design incorporates only two propellers, one for the PS and one for the first meter of the TS. The TS propeller is mounted at the end of the axle and the PS propeller is mounted one meter behind it. The TS propeller has the same dimensions as the TS propeller from the DS design, while the PS propeller is designed in the same fashion as the DS propeller, but with a radius of 0.25m from the axle to the furthest edge.

4. Counterweight

The counterweight for the PS design must be far larger that the counterweight for the DS design. This is because most of the weight of the axle and propellers exists far away from where the carriage meets the rails. This results in a higher tipping moment on the carriage that threatens to derail the carriage. To overcome this, a large counterweight will need to be mounted on the carriage opposite the axle. The exact weight of this counterweight will be determined after the final material and design selections are made.

VI. Materials

1. Carriage

A major design choice is in the material used to create the carriage. The CMS design used a combination of stainless steel for the frame and fiberglass for the panels. The advantage to using stainless steel is its strength and rigidity. The disadvantage is in the Eddy currents generated when the system is moving in a magnetic field. The Eddy currents provide a resistive force that raises the power necessary to move the carriage. To combat this, the tubing used to make the frame should be made of fiberglass. Fiberglass structural elements provide similar material properties as steel while not producing any Eddy current effects. The disadvantage to fiberglass is the holes used to connect the tubes together must be precisely drilled to avoid errors in the position of the central axle.

2. Gears

Prefabricated Gear Reducer vs. Self-Made

The first decision with respect to the gears is whether or not to use a prefabricated gear reducer. Using one would eliminate any concerns regarding lubrication of the gears and would provide a larger gear reduction that can be practically achieved using individual gears. The disadvantage is that most commercially available prefabricated gear reducers use cast iron cases. Unlike stainless steel, where the only worry is Eddy currents, cast iron actively interferes with the magnetic field due to its high relative magnetic permeability. This all but precludes the use of a prefabricated gear reducer unless one can be found uses a material with a relative magnetic permeability close to one.

Stainless Steel vs. Nylon

Assuming a prefabricated gear reducer is off the table, the next question is in choosing the material for the gears. Two options exist that each have their own strengths. The first option is stainless steel. Gears made of stainless steel have a long life span, but introduce Eddy currents. The second option is nylon. Nylon gears have a shorter life span, but have the benefit of not being metallic and therefore would not produce Eddy currents.

3. Main Axle

The main axle must be made of a sturdy material that will bend very little along its length. To that end, two materials spring to mind. The first, stainless steel, has the same disadvantage as it has always had in this application (Eddy currents). The other option, carbon fiber, is expensive, but also has mechanical properties as good as steel at a fraction of the weight. Weight is an important consideration as it determines how much power the toothed pulley wheel needs to be able to transmit to move the rest of the system.

4. PS System Materials

The constraints on materials for most of the carriage that exist for the DS system are not applicable to the PS system. As most of the carriage is outside the magnetic field, choosing non-metallic materials is less of a concern. To that end, it may be easier to use steel t-slotted framing for the frame, as was used in the CMS system. Also, a prefabricated gear reducer would no longer be a problem, giving more accuracy to the movements as a result of slower movement. With respect to the motors, as there will be a minimum of magnetic field that will reach far enough to affect the motor, an electric motor should be considered as it can provide more consistent power. It may also be possible to eliminate the gear reducer for the axle system and simply use a high precision servo motor.

While the constraints on the carriage are lessened, the constraints on the components entering the magnet are even more important. From a weight perspective, it makes sense to decrease the amount of weight trying to tip over the carriage. To that end, it may be wise to consider using all carbon fiber materials for the propellers and c-channel. The bearings are commercially produced and may not be available in non-metallic materials.

VII. Sources of Error

Due to the small nature of the particles being measured, the requirements for positioning of the magnetic measurement system are rather precise. Because of this, each source of error needs to be address, and, if possible, eliminated.

1. Gear Backlash

All gear systems have a small amount of error inherently present called backlash. This error arises from the small gaps that exist when two gears mesh. When the first gear turns, there is a small distance that it must travel before it engages the second gear. This error is intensified by the use of an extended gear train, as each gear interaction produces its own error. As the proposed system has two gear trains, this is a source of concern. To mitigate this error, the system will use the angular and linear position encoders on the propellers and the rails respectively to provide the control system with real-time data so minor adjustments can be made continuously to ensure proper positioning of all the moving parts.

2. Gear Wear

Another issue to consider with regard to gears is the wear they experience over long-term use. This is less of a concern for stainless steel gears, as their high-strength nature combined with the low speed application would result in slow, negligible wear. In contrast, wear would be a significant problem for nylon gears as they are meant for use in especially low-intensity applications. Nylon gears would need to be replaced often and may not suit the requirements of this system.

3. Rail Inaccuracies

A separate study is underway regarding the straightness of the rails with respect to the absolute reference frame and with respect to each other. The preliminary results of this study indicate that the rails have errors on the order of as much as 0.03” (762 µm). This error will cause the central axle to deviate from its starting orientation as it moves down the bore. This movement will be slight; however it must be taken into account when recording the location of where the measurements are taken. Alternatively, the error could be absorbed by having an onboard system to correct the error in the position of the axle, but such a system would need to be active and autonomous. The cost and difficulty of implementing such a system makes it impractical.

4. Torque on Propellers

One source of error that caused some concern in the CMS measurements was the torque on the propellers caused by gravity. This torque may have changed the angular position of the propeller as it revolved. To eliminate any concern regarding this phenomenon, the propellers for this design will have the central axle running through the center of gravity, so no net torque will affect the location of the propellers.

VIII. Next Steps

A few things still need to be considered for this design before it can be finalized.

1. Bearings

The current CAD model calls for mounted ball bearings raised on blocks to the proper position to mesh with the other gears. The blocks introduce an additional challenge and possible source of error and could be eliminated by cutting holes in the platform to accommodate all of the gears or by eliminating the platform by embedding bearings in the exterior panels.

2. Air Supply

A part of the design that has not yet been incorporated is a way to provide air to the motors. This might be accomplished using a rack of air regulators with an onboard air tank or an air tank outside the solenoid with a tube running to an onboard rack of air regulators.

3. Analyses

Following the initial completion of all aspects of the preliminary design process, a vibration analysis should be performed to ensure the system will not suffer from excessive vibrations that would slow down the measuring process. Additionally, an error/tolerance analysis should be performed to ensure the system meets the precision requirements once these requirements are finalized.

IX. Conclusions

A preliminary design for a magnetic measurement system for the detector solenoid of the Mu2e experiment has been devised. This system provides for accurate control of the motion of the carriage along the precision rails and the motion of the propellers. It also incorporates a minimum of metallic materials to minimize the effects of Eddy currents on the system. The preliminary design must now go through an iterative refining process to work out any prototyping issues and to eventually arrive at a final design before construction can begin.

The production solenoid design meets many of the requirements set forth for a magnetic measurement system for the PS; however, much of the design comes from the DS design. This similarity robs the system of unique features that could make it better suited for the PS or cheaper to manufacture. The PS design should be retooled to provide the optimal magnetic measuring system for the PS, perhaps with an eye towards the CDF design.

X. Acknowledgements

I would like to acknowledge the contributions of a few people who aided and supported me during my time this summer at Fermilab. First, my supervisor, Mike Tartaglia, provided me with a fun and challenging assignment and for lent me his expertise each time a new hurdle seemed insurmountable. His associate, Giuseppe Gallo, provided additional, crucial details about the rails that informed my design process and provided meaningful feedback on my designs that helped me optimize them.

I would also like to thank Dianne Engram, Linda Diepholz, Elliott McCrory, and the rest of the SIST/GEM team that provided me not only with the opportunity to come back to Fermilab for my third summer, but also for the amazing support that have given me throughout the summer.

Appendix

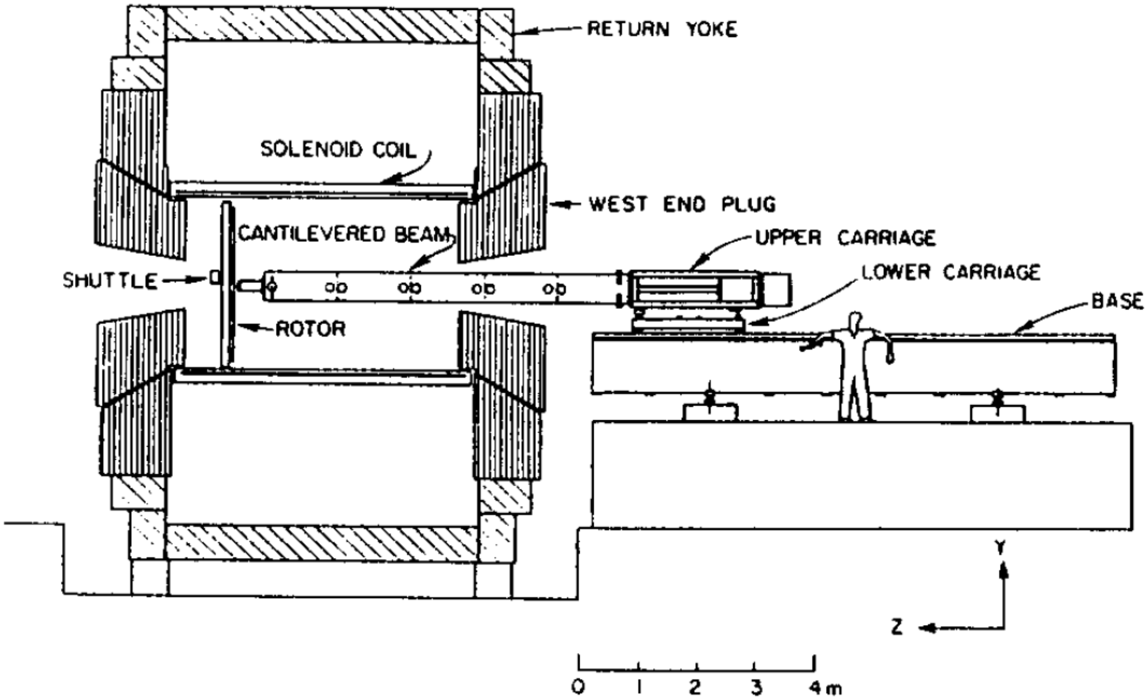

Figure 1: The CDF Magnetic Measuring System

Figure 2: The CMS Magnetic Measuring System

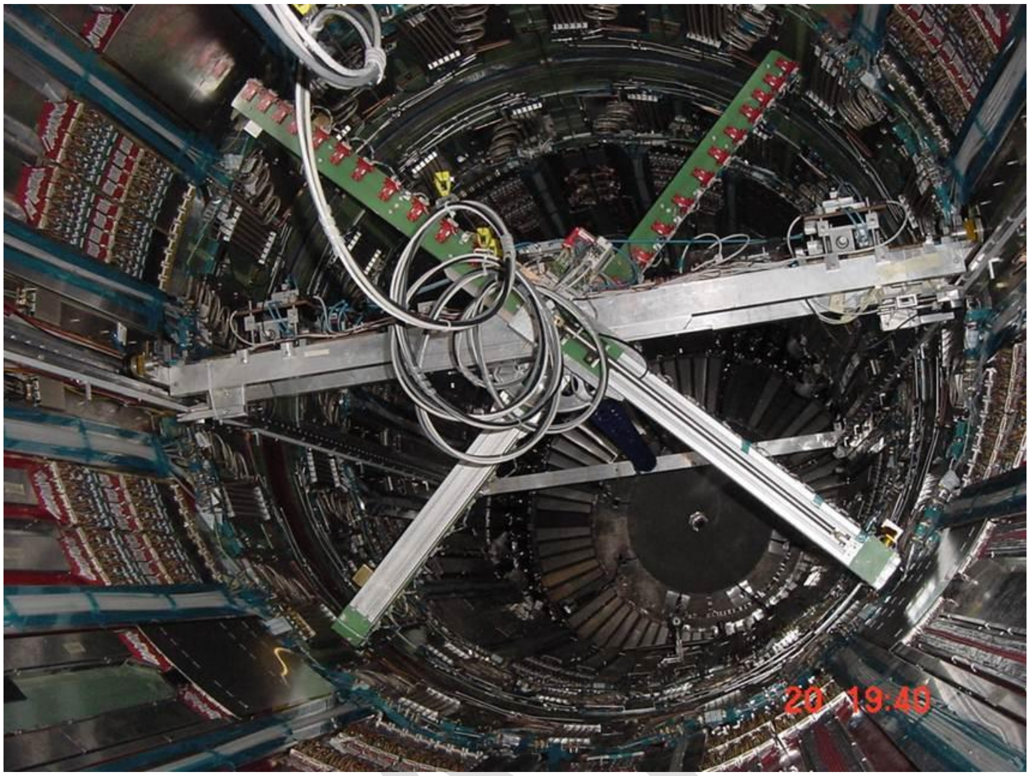

Figure 3: The ATLAS Magnetic Measuring System

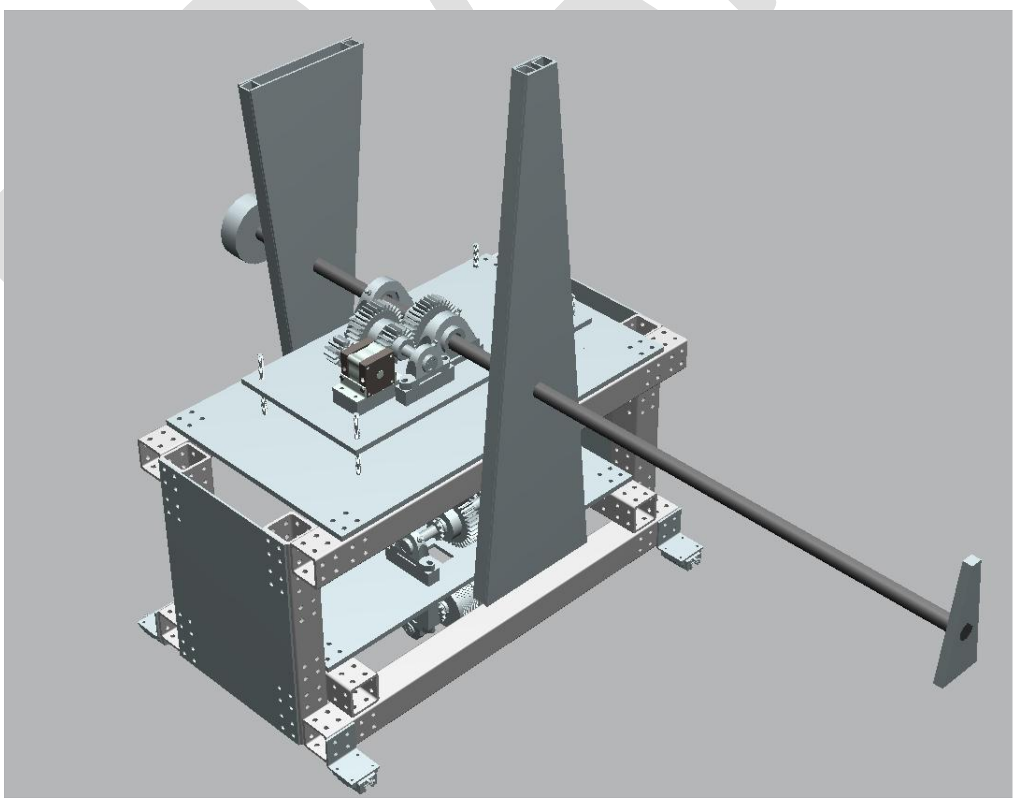

Figure 4: The Preliminary DS Magnetic Measuring System Design

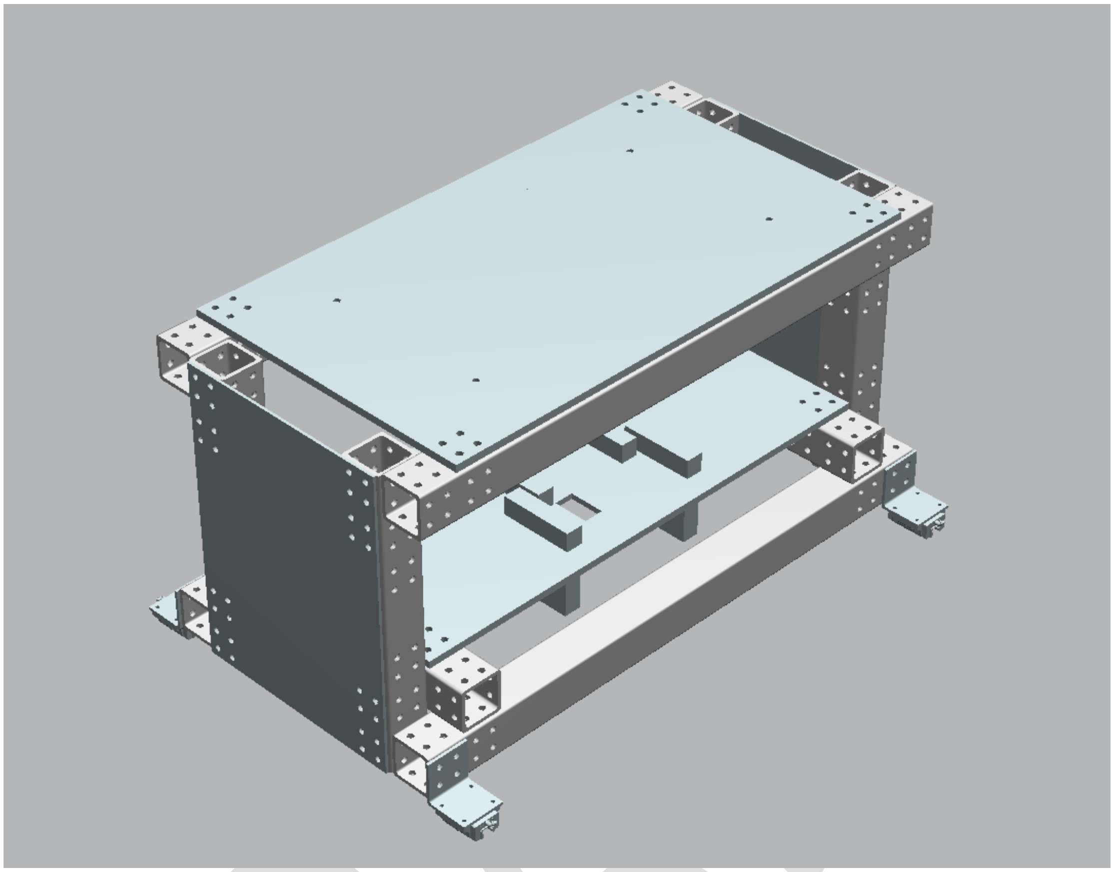

Figure 5: The basic elements of the DS carriage

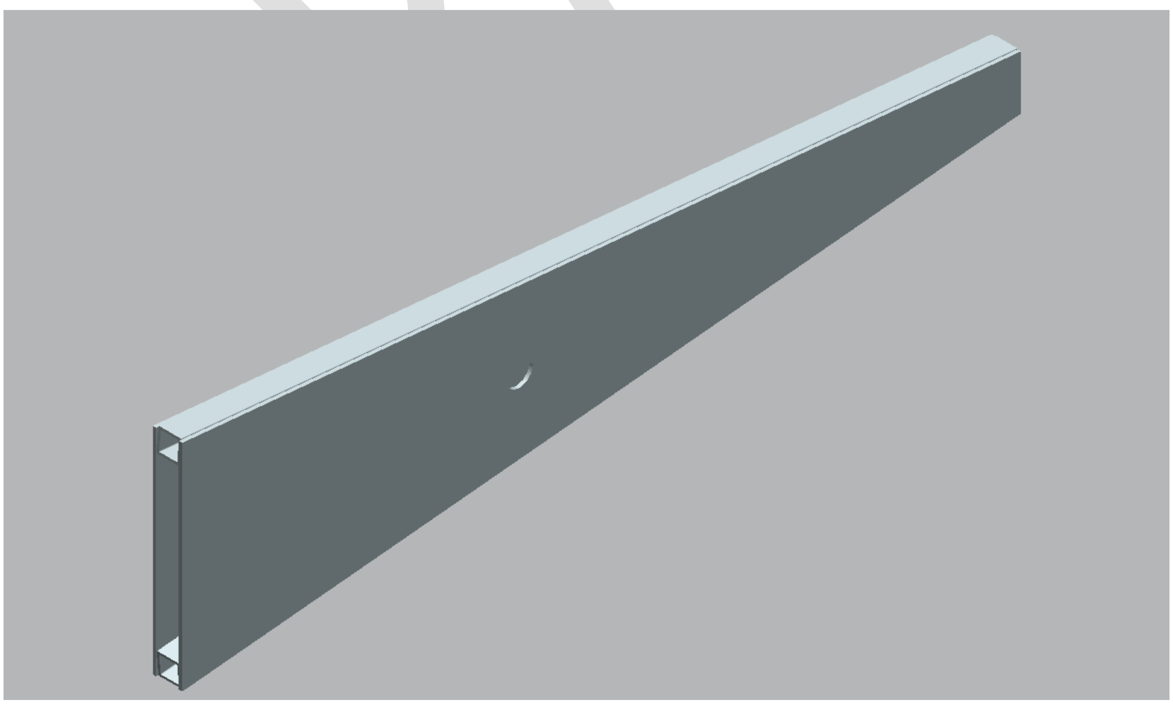

Figure 6: The large propeller

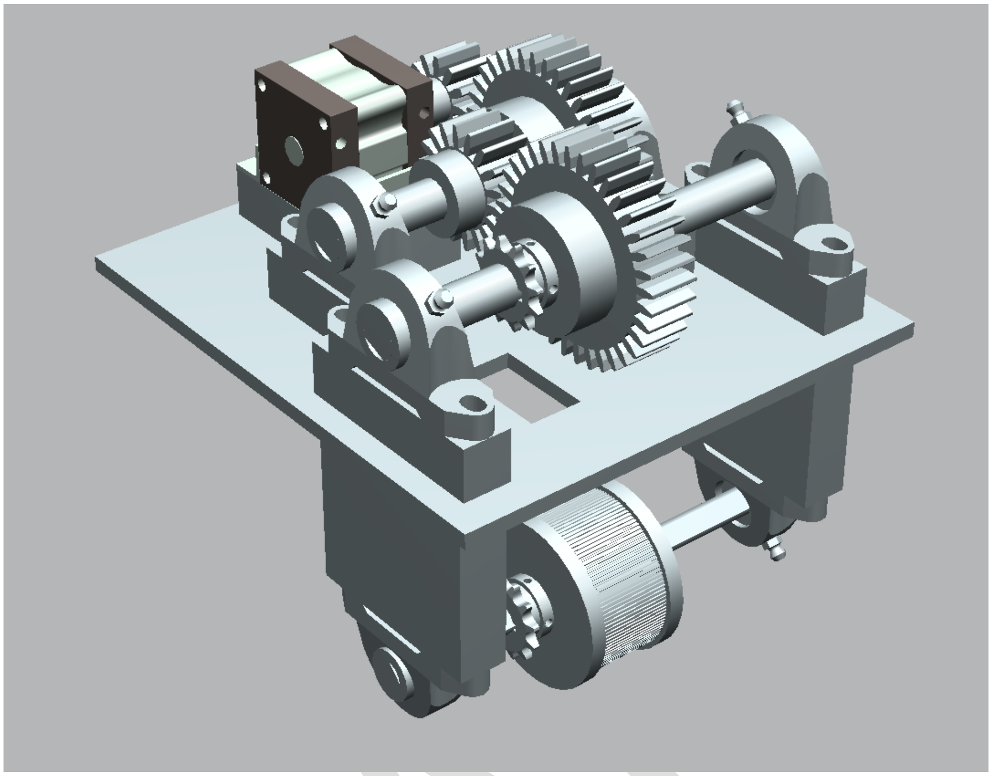

Figure 7: The carriage drive system

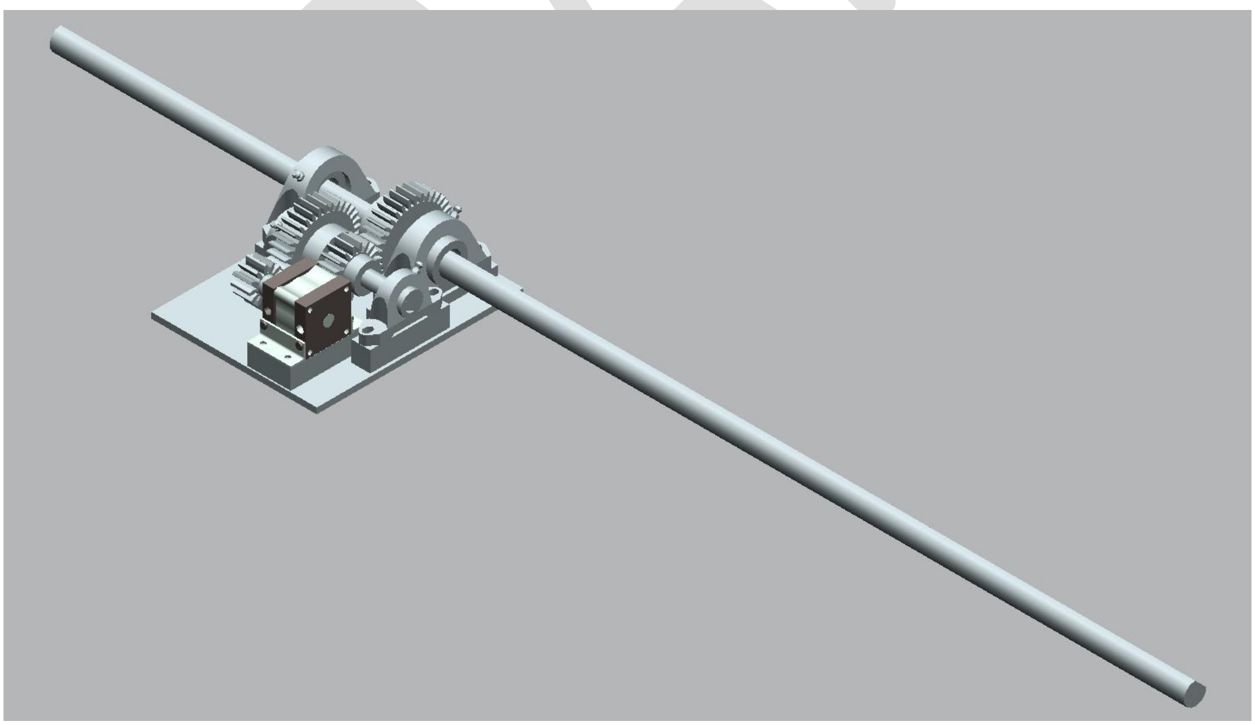

Figure 8: The propeller drive system

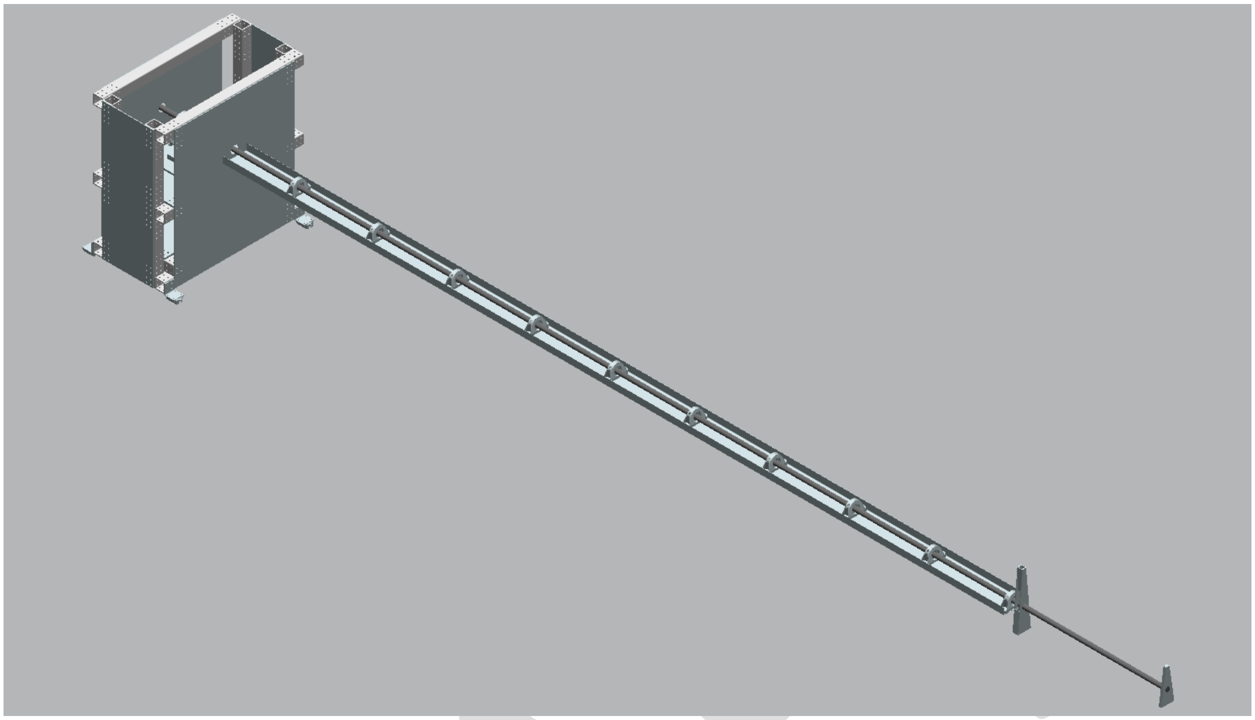

Figure 9: The Preliminary PS Magnetic Measuring System Design

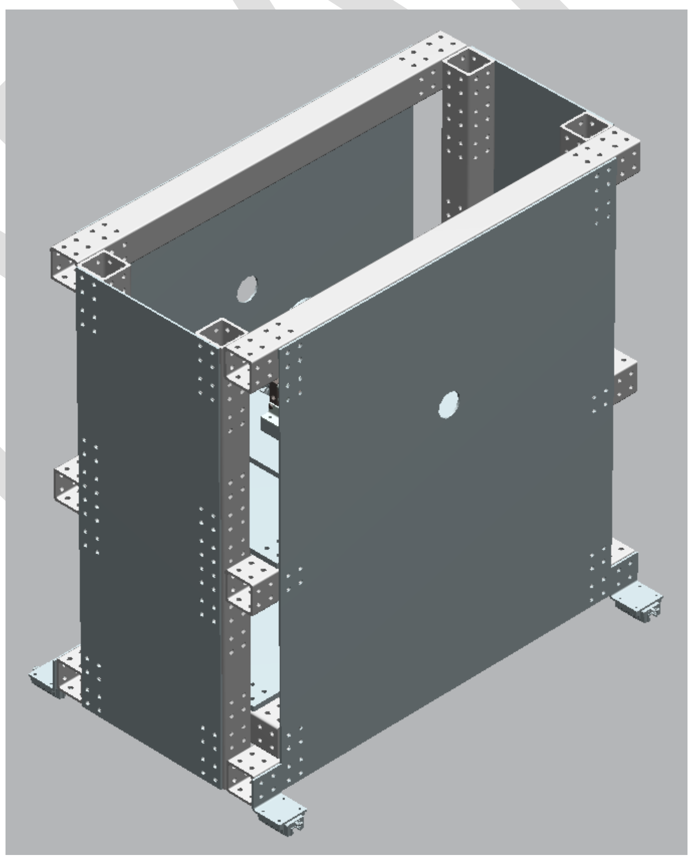

Figure 10: The basic elements of the PS carriage