

The Zero Gravity Mass Measurement Device

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The Zero Gravity Mass Measurement Device (ZGMMD) provides the ability to quantify the mass of objects, including live animal specimens, in a microgravity environment. There are currently no mass measurement devices available on the International Space Station (ISS) that can accurately measure objects with a relatively low mass. The fundamental principle behind the ZGMMD is Newton's second law, which states that the acceleration of an object is proportional to the resultant force acting on it and inversely proportional to its mass. With the assumption that mass does not change with respect to time (which is reasonable when considering the timeframe in which measurement of the mass is occurring) by utilizing Newton's second law, the mass of an object can be derived by quantifying both the acceleration and the forces acting upon it ($m = F/a$). In the ZGMMD the mass (m) is derived from the force (F) measured by load cells, and the acceleration (a), which is a known entity exerted by an actuator. The ZGMMD Phase I prototype was used to investigate measurement accuracy and precision and to demonstrate the basic feasibility of using mass acceleration to determine the mass of samples less than 1kg. Prototype testing demonstrated that a range of masses from a few grams to 1kg could be readily determined with acceptable accuracy and precision. The initial ZGMMD prototype demonstrated the ability to provide an accuracy of +/- 0.1 grams for masses less than 20 grams and 1.0% of sample mass for masses greater than 20 grams, and a repeatability of +/- 0.1 grams. The prototype was also used to test specimen mounting and ease of use. Results from Phase I testing are being used to further improve accuracy and precision in addition to refining a flight compatible design.

Nomenclature

ZGMMD	=	Zero gravity mass measurement device
ISS	=	International Space Station
COTS	=	Commerical-off-the-shelf
MSG	=	Microgravity Science Glovebox
EDU	=	Engineering Development Unit
G	=	Gravities, as a unit of acceleration
g	=	grams

I. Introduction

The Zero Gravity Mass Measurement Device (ZGMMD) will provide the ability to quantify the mass of objects, including live animal specimens, in a microgravity environment. There are currently no mass measurement devices available to the ISS that can accurately measure objects with a relatively low mass, such as live rodent specimens. The ZGMMD provides a fundamental capability (measuring the mass of an object) that would increase the capabilities of NASA's fundamental space biology program.

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A significant amount of ground-based biology research has occurred that used mass measurements as a fundamental data parameter. Zero gravity mass measurement capabilities must be provided to compare on-orbit results with previously conducted ground experiments. Recommendations provided to NASA as part of the National Research Council (NRC) decadal survey include increasing life science research capabilities of the International Space Station (ISS), with an initial focus on rodents as the primary non-human, mammalian model for studies of physiology in space. At the present time, many of the most fundamental and essential laboratory tools upon which experimental procedures depend are lacking. Foremost among these is a means of measuring the mass of research animals, which is required for evaluating their health status, growth, and for calculating dosages that will be used in experimental and/or therapeutic manipulations (including anesthesia and drug doses). Experimental procedures are restricted without an appropriate mass measuring device, one of the most basic instruments in any biology laboratory.

Previous experiments on-orbit have been unable to provide mass data for specimens, or required that the tissue be preserved and returned to the ground for analysis. Making specimen measurements without the significant time delay required for retrieval of samples from on-orbit to weigh on the ground will improve the quality of the data obtained as it avoids the physiological degradation observed in specimens preserved for long periods in less than optimal storage environments.

II. Theory of Operation

The measurement of mass in microgravity is challenging. In the absence of a significant gravitational field, the most direct way to measure mass is through inertia. The ZGMMD operation is based on Newton's second law of motion, which states that a force on an object is equal to the mass of that object multiplied by the acceleration. The mass of an object can be determined if the force and acceleration acting on that mass is known. ZGMMD drives a specimen sample along a rail with a predetermined acceleration profile and measures the resultant force on the object being measured to determine its mass (Equation 1).

$$\text{Mass} = \text{Force} / \text{acceleration}$$

Equation 1

Figure 1 shows the basic configuration of the ZGMMD device.

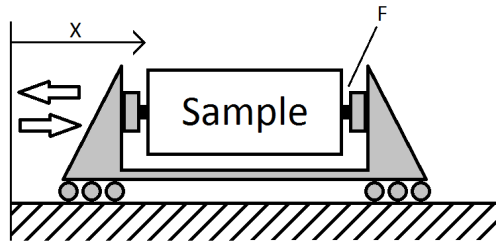


Figure 1. Figure showing basic concept of ZGMMD. The sample is moved at a known acceleration and the force on the sample is determined through the use of force sensors.

There are multiple approaches to inertial mass measurement. We evaluated two approaches to generate force: linear acceleration and angular acceleration. Each offers significant advantages and disadvantages, but we chose linear acceleration because we believe it presents the lowest development risk, and was likely to result in the most compact instrument.

Further, we have chosen to use fixed acceleration, with force as the measured dependent variable. The primary reason for doing so is that, given a typical "stiff" mechanical system, controlling sample acceleration is significantly simpler than controlling sample force. Commercial-off-the-shelf (COTS) motion control systems typically offer accurate acceleration control, but have at best very limited built-in

ability to control force. Using a fixed acceleration over a specified distance also limits the maximum drive speed, whereas the speed of a fixed-force system would be inversely proportional to sample mass, and therefore might be quite high with small masses.

A further design choice was whether to make force measurements in both directions of motion, or in only one. Measuring in both directions, and deriving mass from the difference of the two measurements, has the advantage of effectively canceling system offset and low frequency offset drift. Offsets arise from both mechanical and electronic causes, and can be large compared to the desired resolution.

A significant design challenge for all balances is accurately measuring loads that are not perfectly centered on the load platform. A common approach is to use a series of beams to transfer the load from the platform corners to a single load cell. Knife-edge pivots minimize friction. While this approach is simple and effective in compression, it would be complex to implement well in both tension and compression, as is required by the ZGMMD. Another technique adopted in some smaller balances is a custom load cell that can tolerate high off-axis loads without significant accuracy loss. However, such load cells are not commonly available commercial products. In addition to handling off-axis loads, the ZGMMD load platform must survive potentially large forces and moments generated by users as they attach and remove samples. All these factors place significant constraints on the ZGMMD load platform design as compared to a typical terrestrial balance, and have led us to adopt a twin load cell approach.

By using two load cells as the sole attachment points between the load platform and the sample carrier, all test mass forces are guaranteed to pass through the load cells. Because the load cells have a very small deflection under full load, on the order of 0.1 mm, they are well suited as structural elements, provided that loads on their side surfaces are limited.

A. ZGMMD Design Philosophy and Requirements

The ZGMMD design philosophy at the start of the project consisted of the following tenets:

1. Specimen Accommodation

- Provide the ability for determining the mass of live rodents.
- Do not adversely affect the health and well being of live research specimens during any phases of operation and test.
- Provide for changes in specimen type and in experiment protocols on orbit.
- Minimize entry into the crew living environment of particulate matter, chemicals, microorganisms and other airborne contaminants during the measurement process.

2. Operations

- Minimize crew time requirements for assembly and operation of the hardware.
- Be modular to permit independent replacement of hardware and software components with minimal impact on the rest of the facility.
- Incorporate commonality to minimize the number and types of components to optimize logistics operations.
- Utilize human ergonomic concepts to minimize crew utilization and maximize crew comfort & safety.
- Maximize the time required between maintenance activities.
- Minimize the difficulty of and the need for on-orbit maintenance, inspection, and repair.

3. Engineering

- Design for minimum risk.
- Minimize mass, volume, and power consumption, with particular attention to the continuing resupply/return mass and volume.

- Minimize the volume of on-orbit stowage required for support and maintenance.
- Utilize flight-proven technologies to the extent that is cost-effective.
- Use increased margins consistent with mission objectives and system constraints, where such measures shall reduce the analysis and test requirements, and result in overall cost-reduction for the program.
- Employ verification by test wherever feasible and practical. Verification by analysis plus inspection or demonstration shall only be used if testing is impractical or excessively expensive.
- Use commercially available equipment and tools where appropriate and cost-effective.
- Be designed to minimize loss of function. Where loss of function due to single-point failures cannot be eliminated, safety margins shall minimize the probability of failure.
- Be designed to be operable and repairable by a Life Scientist (PhD or MS) flight crew member.

The first stage of the ZGMMD development was to create a flight specification document to identify and capture applicable specifications for operating the ZGMMD in the Microgravity Science Glovebox (MSG) or similar facility on the ISS. These requirements included system design and performance requirements derived from input by potential users of the system and a set of ISS facility interface and safety requirements derived from NASA interface and safety specifications. The two primary performance parameters for ZGMMD are accuracy and precision. Accuracy represents how close the measured mass is compared to the actual mass of the sample being evaluated. Precision is a measure of how repeatable the determination of the sample mass is. However, many additional requirements had to be taken into account during the design process including measurement resolution, tare, calibration, specimen accommodations, operational environments, and mass, power and volume limits.

III. Phase I ZGMMD Prototype Development and Testing

Upon completion of the ZGMMD specifications, a Phase I prototype was designed and fabricated to validate hardware and protocol concepts and to allow refinement of design and control parameters. The Phase I prototype was designed for a mass measurement range of 5 to 1000 grams.

A. Hardware configuration overview

The ZGMMD Phase I prototype was designed around a motor and a linear slide assembly. These two components are key to the device, applying the necessary acceleration to the sample. The rail length of 25.4 cm (10 inch) was calculated to allow data sampling for at least 0.25 seconds at a constant 1G acceleration. It was desired that the linear slide have few moving parts, low vibration, low friction, and require no maintenance. These criteria ruled out many conventional linear rails that use ball bearings. An Igus DryLin linear guide was used in the prototype. This system uses maintenance-free, lubricant-free, PTFE-based material that rides directly on an aluminum rail. The acceleration of the linear slide is driven by a stepper motor. This motor moves a timing belt attached to the linear slide. Predetermined acceleration profiles can be sent to the motor controller and the linear slide moves accordingly. Opposite the motor, a pulley keeps tension on the belt. To minimize backlash in the belt drive (and prevent error from unexpected linear slide motion) at least 50N of tension is maintained in the belt by two springs.

On the linear slide is the mechanism for actually measuring the sample mass. Two load cells measure how much force is transmitted to the sample, which is firmly secured in the sample holder. Between one and three load cells were initially considered for supporting the sample holder and measuring the force required to move it. A single load cell has the advantage of simplicity, but can easily give inaccurate results or take damage if off-axis loads are present. This is a problem during measurements as well as when samples are being manually fastened to the sample holder. A two-load-cell arrangement offers a significant resistance to off-axis horizontal loads, and the geometry of the load cells offers some support for vertical loads. Using three load cells to support the sample would be the strongest option, but offers

diminishing returns in exchange for increased cost, increased data rates, and longer computation times. A set of two load cells was chosen for the ZGMMD Phase I prototype.

Several geometries were also considered for the sample holder, which needs to be lightweight and firmly constrain a variety of sample shapes so that they move smoothly with the linear slide. A plastic vial used by a number of animal researchers was selected as a preliminary baseline sample container. A “V” shaped holder was developed with elastic cords to hold the sample container in place. This design worked well with cylindrical samples and is compatible with a large variety of other shapes.

Together with the motor, linear slide, and belt tensioner, the total length of the ZGMMD prototype was ~66cm (26 inches). The width and height of the device were chosen based on a 15cm (6 inch) cube maximum sample size. For simplicity, the structure surrounding this volume was made out of 80/20 framing system components. Panels were included to enclose the moving parts on the sides and a clear protective cover was made to open for easy access to the controls and sample. A diagram of the prototype is shown in Figure 2. Photographs of the prototype are shown in Figure 3.

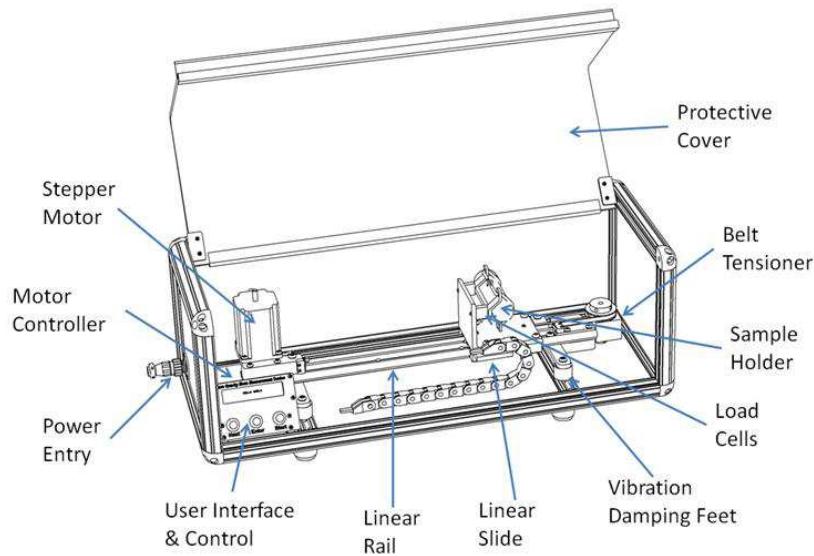


Figure 2. Diagram showing ZGMMD components and configuration.

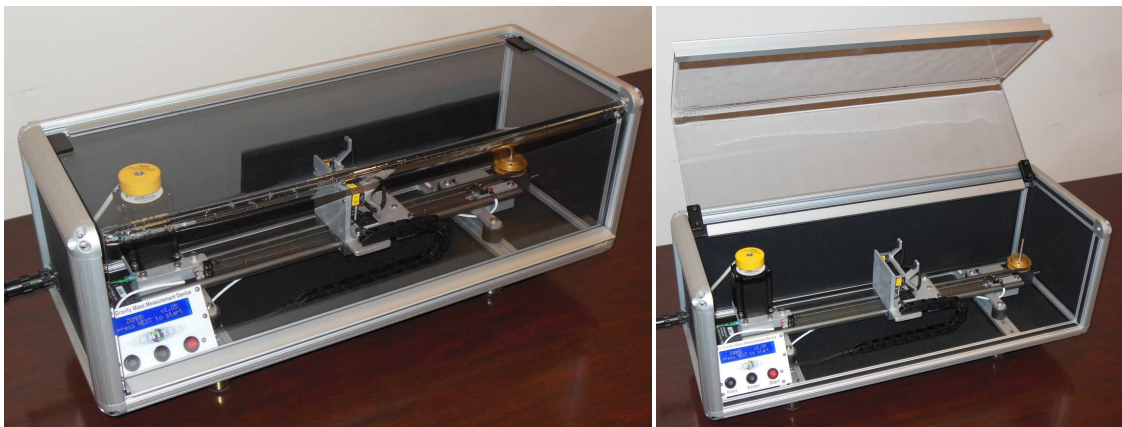


Figure 3. ZGMMD Prototype with cover in closed (L) and open (R) positions. The Phase I prototype was developed as a test unit and was not configured to meet MSG physical interface requirements.

B. ZGMMD Actuator and Drive

The primary purpose of the actuator/drive is to accelerate the ZGMMD sample at a controlled acceleration. A key characteristic for good performance is smooth linear acceleration applied to the specimen. The acceleration level refers to the accelerations that are imparted on the sample being measured. During the measurement process the samples are accelerated in both the + and - directions along the axis of travel. During Phase I the levels of accelerations tested were 0.5, 1.0, and 1.5 G's. One g level is equivalent to the downward acceleration provided at sea level on the Earth's surface (9.81m/s^2).

The actuator/drive comprises several components: motor, motor driver, linear slide, belt, and pulley. The motor provides torque to a pulley mounted on the shaft of the motor, which interfaces with a toothed belt (Figure 4). The toothed belt is inelastic, and provides a positive interface with the gear to minimize any play. The belt travels around a second pulley at the far end of the linear slide and is under constant high tension to prevent any slack in the belt. The belt also interfaces with a carriage, which is mounted to the linear slide (shown in Figure 5).

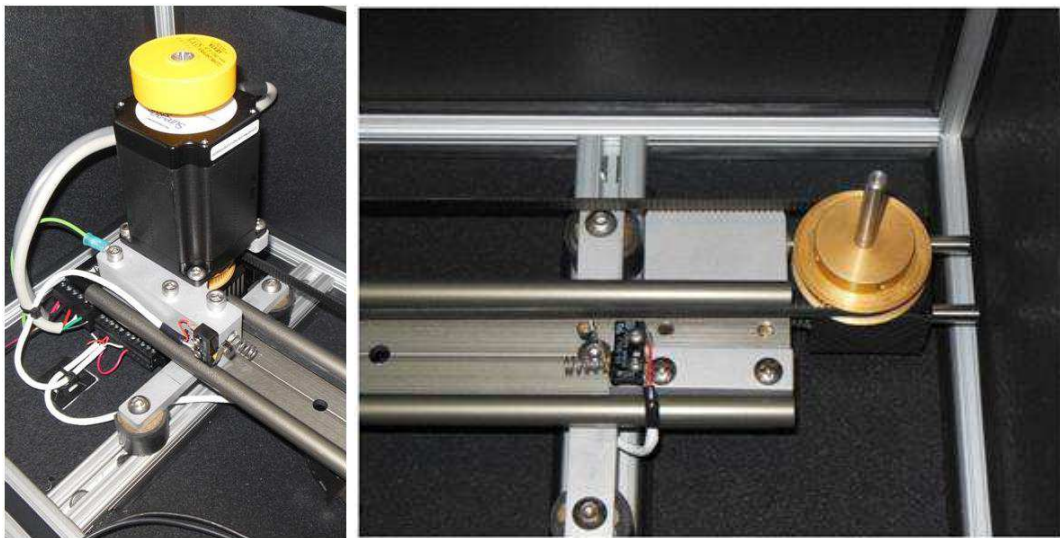


Figure 4. Phase I prototype Actuator/Drive.

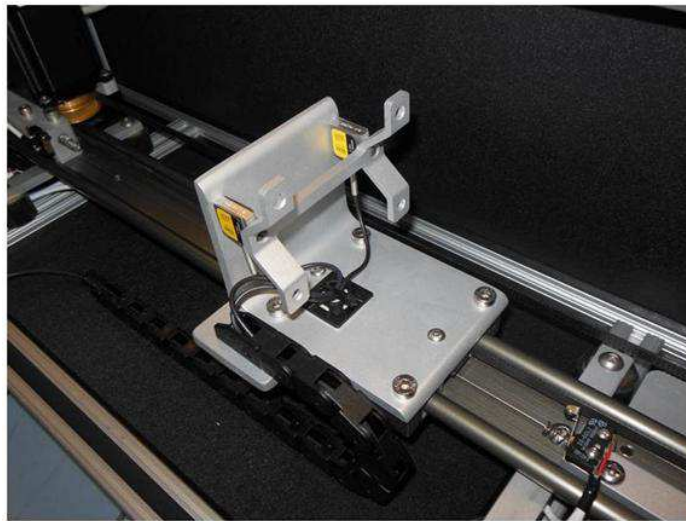


Figure 5. Specimen interface mounted to load cells, connected to a carriage on the linear slide.

Several tests were conducted using the ZGMMD prototype. Variables included three different acceleration levels (0.5 G, 1.0 G and 1.5 G), three different calibration masses, and different standard masses. Each series of tests consisted of several repeated measurements of a standard mass. Error was determined by subtracting each measurement from the standard mass. Average error was determined by averaging all the errors from one set of measurements with a given standard mass. Precision was determined by calculating the standard deviation of each set of measurements at a given standard mass.

Calibration of the ZGMMD takes approximately five seconds (after a calibration mass is placed in the sample holder and is dependent on the G level selected). The time it takes for mass determination is comparable to that for calibration, and is on the order of five seconds. The longer the ZGMMD takes to evaluate a sample, the more the precision, and possibly the accuracy, increases.

The average accuracy observed during Phase I testing over the range of operation from 100 to 1,000 grams is shown in Figure 6, and could be less than 0.5% of the measured mass when acceleration and tare were optimized. Measured masses included 95.8g, 221.9g, 367.8g, 678.1g and 977.2g. For mass less than 100 grams, the accuracy was typically less than 1%, and is shown in Figure 7. Measured masses included 13.1g, 25.1g, 44.6g, 46.0g, 67.1g, and 95.8g.

Precision for the Phase I prototype was generally good. In the range from 100 to 700 grams measurement difference was less than 0.2 grams, while above 700 grams the measurement difference increased to about 0.3 grams (Figure 8). This increase is expected for a balance with two orders of magnitude range. ZGMMD's precision as a percentage of the mass being measured is typically less than 0.05%, with it trending higher at the lower end of the mass range, which was to be expected as small differences reflect higher percentages at low mass readings. The precision for masses less than 100 grams is typically less than 0.3 grams and is shown in Figure 9. This reflects the low mass performance with 1.0 g accelerations; however, when the acceleration is increased to 1.5 G, the precision increases dramatically to typically less than 0.1 grams, which is shown in Figure 10.

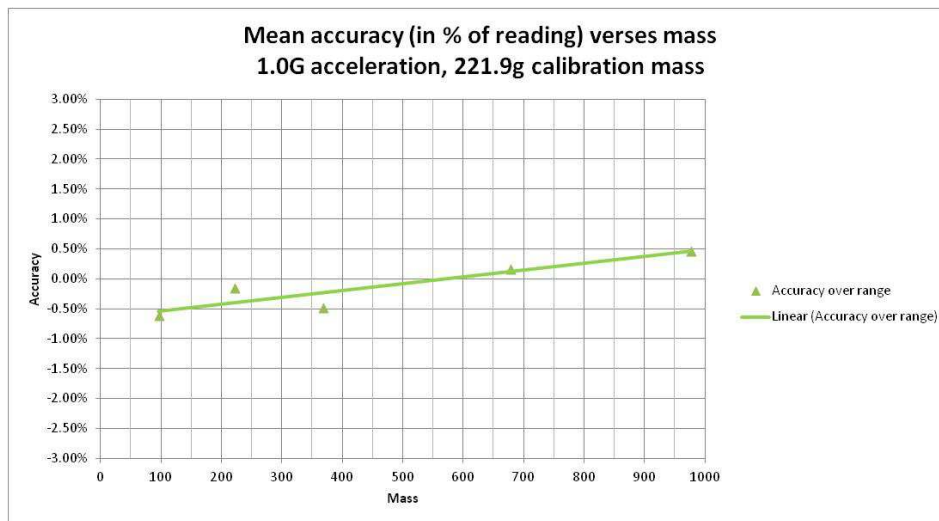


Figure 6. Phase I prototype accuracy for samples between 100 and 1,000 gram.

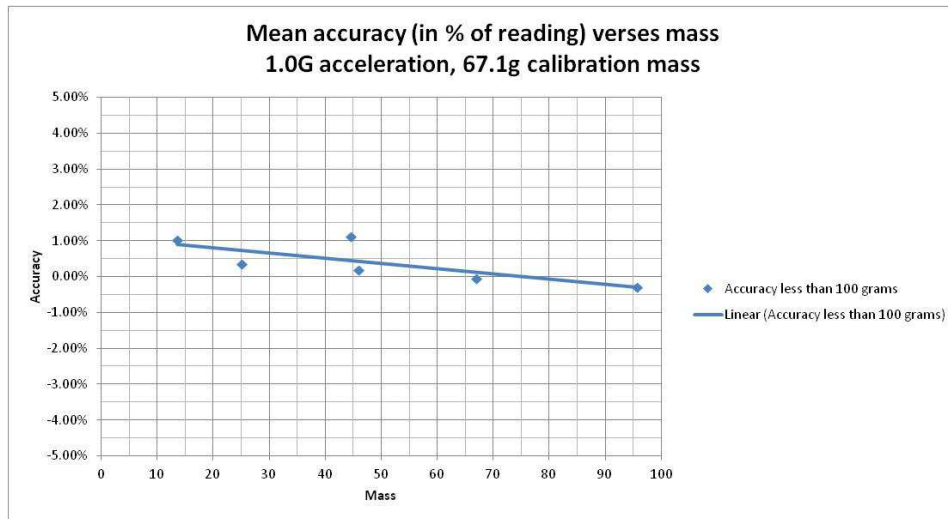


Figure 7. Phase I prototype accuracy for samples less than 100 gram.

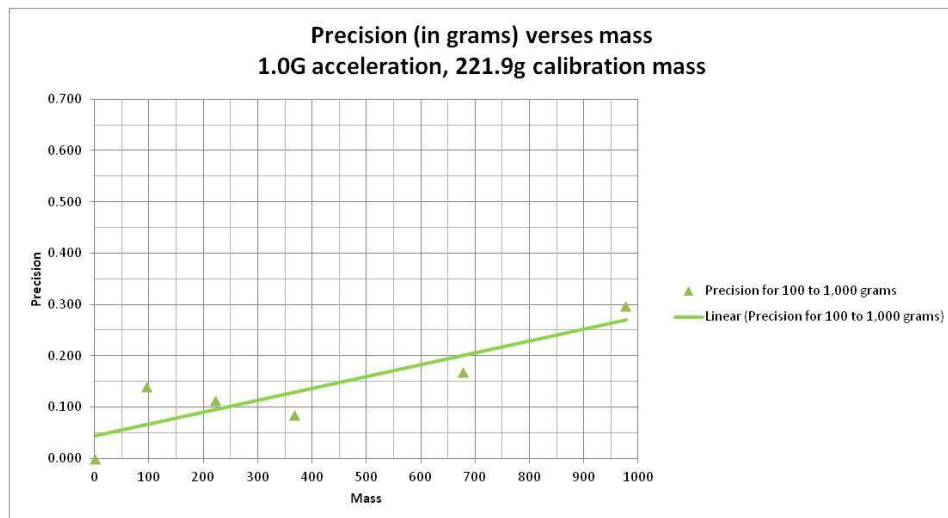


Figure 8. Phase I prototype precision in the range of 100 to 1,000 grams.

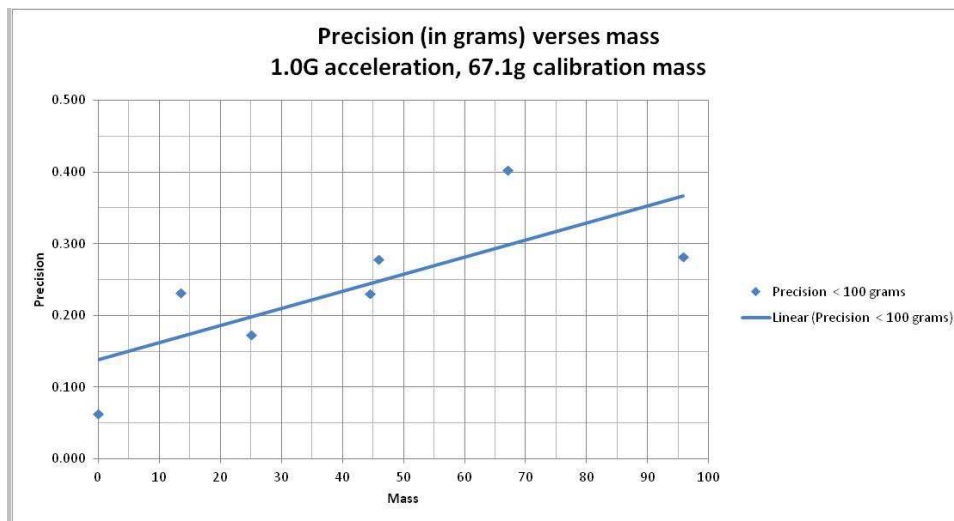


Figure 9. Phase I prototype precision for samples of less than 100 grams, with 1.0 g acceleration.

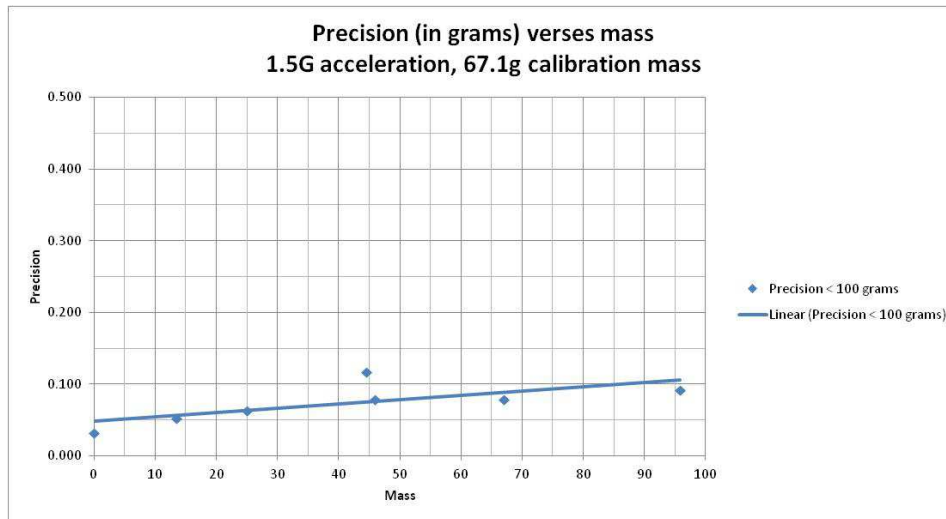


Figure 10. Phase I prototype precision for samples of less than 100 grams with 1.5 g acceleration.

Figure 9 and Figure 10 show how acceleration of the sample can impact precision. The higher the acceleration, the larger the signals being monitored by the force sensors. If the same error is present, then the result of increasing the acceleration has the effect of increasing the signal-to-noise ratio, providing more consistent readings, which leads to increased precision.

As previously mentioned, both the calibration mass and the acceleration level play important parts in the performance of the ZGMMD. As could be expected, using a calibration mass closer to the expected mass provided better accuracy. The impact of the acceleration level used during testing on measurement accuracy and precision was of particular interest. Observations were that at lighter masses accuracy was improved by increasing acceleration, while for heavier masses an acceleration of 1G tended to result in the best accuracy. Decreased accuracy observed for some of the heavier masses was due to some distortion of the specimen restraint elastic bands that allowed the specimen holder to shift slightly during measurement. Precision was greatest at the higher acceleration levels, though again it was impacted at higher measured masses by movement of the specimen holder during measurement. **Error! Reference source not found.** More rigid mounting of the specimen holder is being addressed as part of the Phase II prototype design effort.

IV. Phase II ZGMMD Prototype Development

During Phase I, the ZGMMD prototype was used to investigate measurement accuracy and precision and to demonstrate the basic feasibility of using mass acceleration to determine the mass of samples less than 1kg. Prototype testing demonstrated that a range of masses from a few grams to 1kg could be readily determined with acceptable accuracy and precision. The prototype testing demonstrated fully the feasibility of the ZGMMD design and identified a design path to increase accuracy and precision during Phase II development of a ZGMMD protoflight unit.

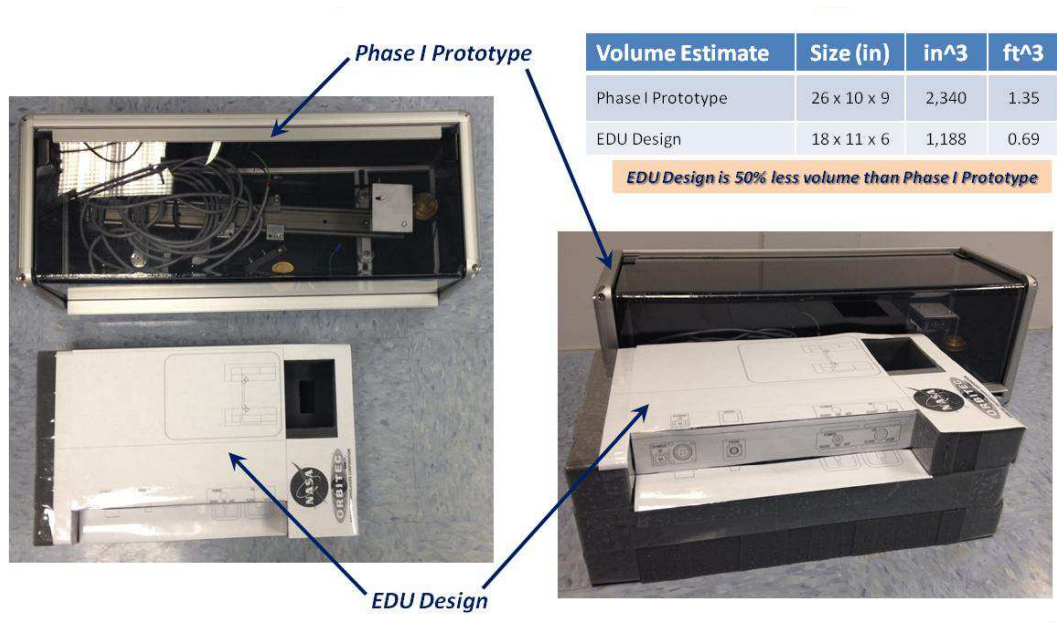
Because the initial application for ZGMMD will be to support small rodent (mouse) research on ISS, it was decided to reduce the maximum target mass for the Phase II development from 1000g to 100g to allow for higher accuracy and precision across the range that would be most applicable to this research. Accuracy and precision requirements for the 100g maximum configuration were modified to;

- a) The ZGMMD shall be able to provide an accuracy of +/- 0.1 grams (with a goal of +/- 0.05 grams) for masses less than 20 grams and 1.0% (with a goal of 0.5%) of sample mass for masses greater than 20 grams.

- b) The precision of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results. The ZGMMD shall be able to provide a repeatability of +/- 0.1grams (with a goal of +/- 0.05 grams).

A. Phase II hardware configuration

The Phase II hardware design represents significant refinement of the Phase I prototype design. As part of the Phase II, a higher fidelity prototype, called an Engineering Development Unit (EDU) is being fabricated. The Phase II size envelope was reduced from the Phase I size envelope (Figure 11) and modified to a flight acceptable configuration. The general configuration of the Phase II EDU design is shown in Figure 12.



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Figure 11. Comparison of Phase II Engineering Development Unit and Phase I prototype configurations. Image shows a ZGMMD EDU demonstration mockup.

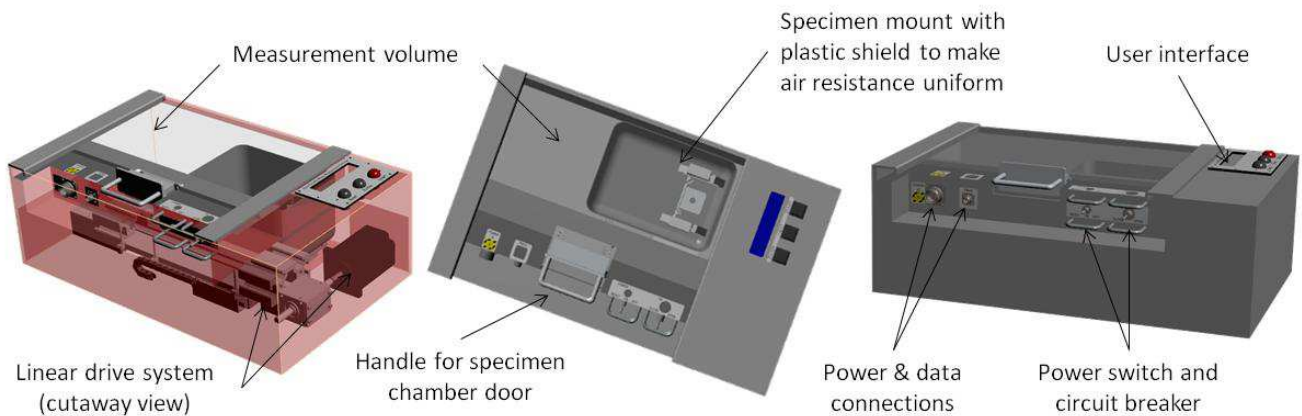


Figure 12. Views of ZGMMD Phase II EDU design.

B. Actuator and Drive

The Phase II prototype includes an upgraded drive mechanism configured with an embedded belt to prevent fouling of an exposed moving belt (Figure 13). After extensive testing of multiple drive and rail configurations, a 4 to 5 inch linear travel configuration was selected as an optimal balance between system precision and overall unit size. The stepper motor provides very precise high resolution control of the motion platform on the rail. The specimen holder will mount to the side of the motion platform with a cantilevered offset to reduce the overall size of the system (Figure 14). Placing the carriage assembly off to the side allows all components to be placed in a rectangular package. This configuration also provides a separate area for the carriage assembly motion, which is better for minimizing potential contamination from live specimens. The linear rail assembly is undergoing extensive tests (Table 1) to determine control and operating protocols that provide the best ZGMMD accuracy and precision.

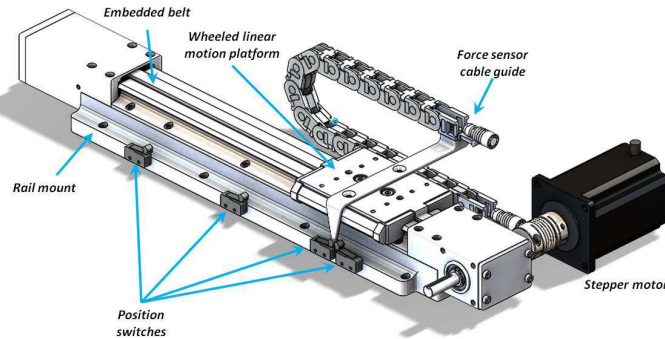


Figure 13. Linear rail and drive mechanism for Phase II ZGMMD EDU.

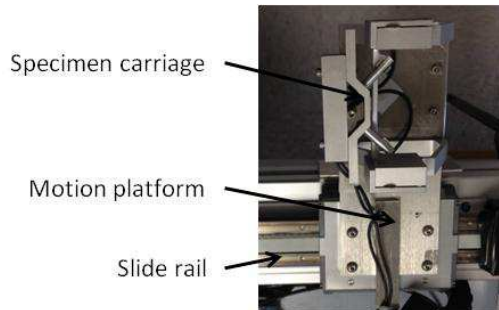


Figure 14. Close up view of offset carriage assembly mount to motion platform.

Table 1. Parameters currently being tested to optimize ZGMMD design prior to fabrication of flight articles.

Parameter	Notes
Acceleration profile	Multiple acceleration levels and profiles
Data collection using flight like microcontroller	Shift testing of control and data acquisition from laboratory to using flight-like configurations
Motors and controllers	Evaluate different types and brands of motors and controllers
Length of traverse	Optimize length for good results and smallest foot print.
Tare mass	Optimize operational performance
Specimen interface	Validate 1-2 baseline specimen holders
Sampling rate and cycles/run	Optimize operational performance
Sets of runs at different times	Test groupings repeated after various delays to characterize hysteresis.
Damping (material & location)	Optimize operational performance
Calibration and operational protocols	Optimize operational performance
Other (e.g., Orientation; Processing algorithms)	Optimize operational performance

Figure 15. The two data lines shown on each plot represent the boundary of data for 10 runs, with the upper line containing the data from the highest response and the lower line containing the data from the lowest response. The ZGMMD requirements and goals are also noted on the plots, with the requirement of ± 0.1 grams (goal ± 0.05 grams) for masses less than 20 grams shown on the top plot, and the requirement of 1.0% (goal 0.5%) of sample mass for masses greater than 20 grams shown on the bottom plot. The requirement is shaded with light blue, and the goal is shaded with darker blue. As seen in these representative accuracy plots, the Belt-Driven linear slide assemblies demonstrated the ability to exceed the requirement goal.

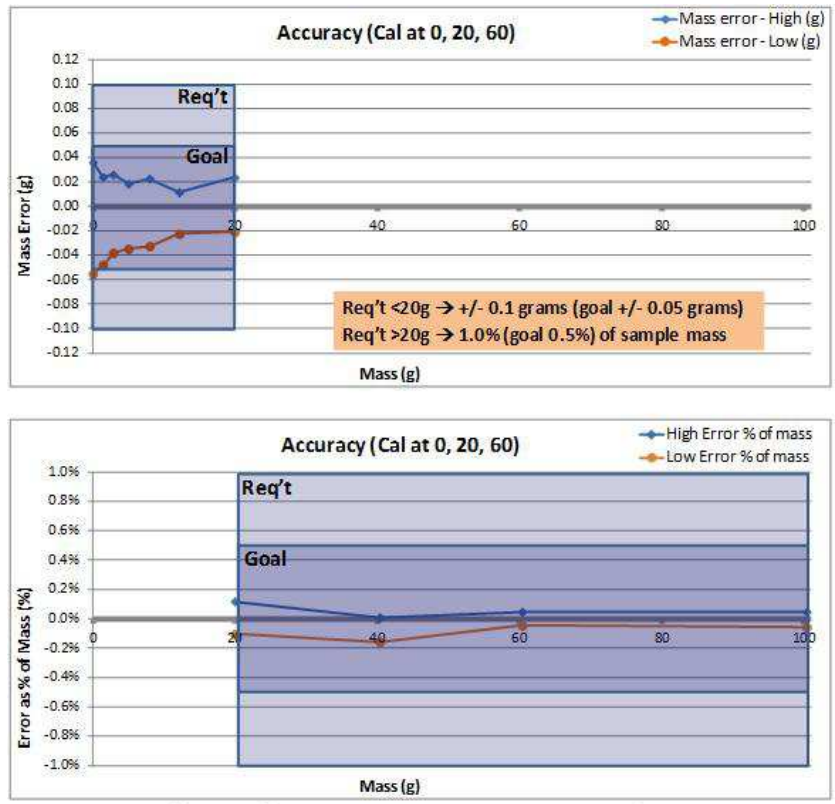


Figure 15. Accuracy plots for linear slide with 4.5 inch travel, 60g tare, and 1.5 G acceleration.

IV. Conclusion

During Phase I, the ZGMMD prototype was used to investigate measurement accuracy and precision and to demonstrate the basic feasibility of using mass acceleration to determine the mass of samples less than 1kg. Prototype testing demonstrated that a range of masses from a few grams to 1kg could be readily determined with acceptable accuracy and precision. It was also used to test specimen mounting and operational ease of use. Testing identified design and operating parameters which are being implemented in the Phase II ZGMMD design to further increase accuracy and precision, as well as to improve the specimen and operator interfaces. The mass range of the Phase II design was reduced from 1000g to 100g to further improve accuracy and precision for small rodent research. The Phase II design is also optimized for operation in the MSG or similar facility and will be fabricated as a protoflight unit.

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