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Space Scale variant for Exploration space vehicles

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Abstract. Measuring mass in weightlessness in space cannot be achieved by a balance or a bathroom scale with load cells. Up to now, astronaut body mass onboard spacecraft, including the International Space Station (ISS) is measured with spring-mass Body Mass Measurement Device (BMMD)'s. As those BMMD's need a large and sturdy frame to stabilize subject body, they are large and heavy. The author group proposed a new smaller device "Space Scale" with laser interferometry acceleration measurement and an inline force sensor with a bungee cord. This paper first reviews the advantage of ISS Space Scale that is oriented for better uncertainties and ease of operation, then evaluate its applicability to smaller spacecraft that are to be used missions further than the low-earth orbit, like cis-lunar orbit, or lunar/asteroid/Mars orbit. Those spacecraft cabin flying these trajectories are in microgravity environment.

1. Introduction

Body mass, 'body weight' on the ground, is the basic index of nourishment, also is an altered body fluid homeostasis indicator under microgravity environment in the spacecraft in low earth orbit. Without periodic onboard medical monitoring and assessment by flight surgeons on the ground, astronauts tend to be too hypovolemic (low in body fluid). Hypovolemia at the time of reentry back to the ground enhances physiologic intolerance including low blood pressure, which might lead to dysfunction of returning crew at emergency landing.

Measuring astronaut body mass in spacecraft in low earth orbit on a regular basis is now a part of space medical operations on the International Space Station (ISS). However, its measurement principle in the microgravity environment has not changed much since the Skylab program in 1970's. Skylab body mass measurement device was based on mass-spring system resonant frequency and developed by Thornton WE et al. at NASA [1].

The apparatus for in-orbit body mass measurement started as payload experiment hardware. Initially, size and volume of the hardware and complexity of operation was not a big issue. When it became part of the periodical systems operation, simplicity of protocol and easiness of hardware manipulation is now more important to save precious crew time on the spacecraft.

Apparently in microgravity, ground-type balance or scale is inapplicable. In the previous space programs, selected quality spring with timer device was chosen to implement a spring-mass system and frequency principle design to derive the amount of mass. Other measurement principles were hard to materialize. In the current ISS program, NASA ISS "SLAMMD" body mass measurement device uses spring-mass system with specially made spring [2]. Instead of timer, acceleration sensor is used to calculate mass. Still SLAMMD needs a rigid frame to oscillate whole human body. It is installed in a standard ISS experiment rack and not easy to deploy, and needs considerable crew time to relocate.

Now it is the time to think about applying modern laser technique to observe distance, velocity, and use force sensors to this old problem of measurement of mass in microgravity. The author's group proposed a new look at this old problem with the current optics technology. We named our device "Space Scale" [3].

2. Medical Requirements

Body mass measurement on ISS is done every month for every astronaut onboard. ISS medical requirement is the base of this periodic body mass measurement. Current baseline instrument is a Russian 'IN' Body Mass Measurement Device in the Service Module of the Russian segment of the ISS. Its design principle is based on resonant frequency of mass-spring system. The Russian device is semi-permanently installed onto the Russian module floor of the ISS. NASA activated a rack-mounted device called SLAMMD in 2006, which measures acceleration of mass in a mass-spring system. These two need a relatively large frame to accommodate a human body, which leads to a permanent installation. From operational view, it is desired that the device to be much smaller and transportable to eliminate mechanical interference with other apparatus in a module, and save crew time to deploy the device.

Thus the first condition for our new device is: (1) Compactness and portability.

A mass measurement requires reasonable precision. In case of human body, required precision is the same as body weight measurement on the ground for medical purpose. Clinical-use devices have precision about 100g, or 0.13-0.2% (weight of the subject centers around 75kg).

To discuss average weight changes over a number of subjects, precision around this range is required: (2) Precision of 0.2% over body mass range (~100kg).

It is ideal to achieve the precision of 0.05kg to be reliable enough to discuss body mass change in the orbit. Accuracy requirement depends on how easy it is to calibrate. Because the measurement is done over a brief time, long-term drift is not an issue, if some means of calibration is available. Practically this is achieved by measuring a calibration standard mass, which is available in the form of metal hardware of known mass in the cabin.

3. Space Scale Ground Model review

Based on "Space Scale" principle [3], prototype ground model was submitted for precision estimation. This design incorporates an attachment of an elastic spring to the vicinity of human body center of gravity, laser interferometry distance measurement that makes it a compact device, and a force sensor to record the tension of the elastic spring. The data showed that its precision generally covers the requirements described above [4].

3.1 Methods

Desk-top bread board model was constructed with simulated subject mass and rubber cord (Fig.1, 2). Microgravity is simulated by use of aerostatic linear bearing. This setup was made for proof-of-concept and estimation of accuracy/precision. Simulated body mass M_{cal} and rubber property values were arbitrary, but large enough to model human body mass measurement. To calculate the value of mass, the acceleration of simulated body when rubber cord was stretched and released was measured by laser interferometry, and the force was recorded by a transducer as rubber cord tension. The relationship of the body acceleration and force between the ISS wall and the astronaut subject gives the value of mass. Details of hardware and measurement description were previously reported [3].

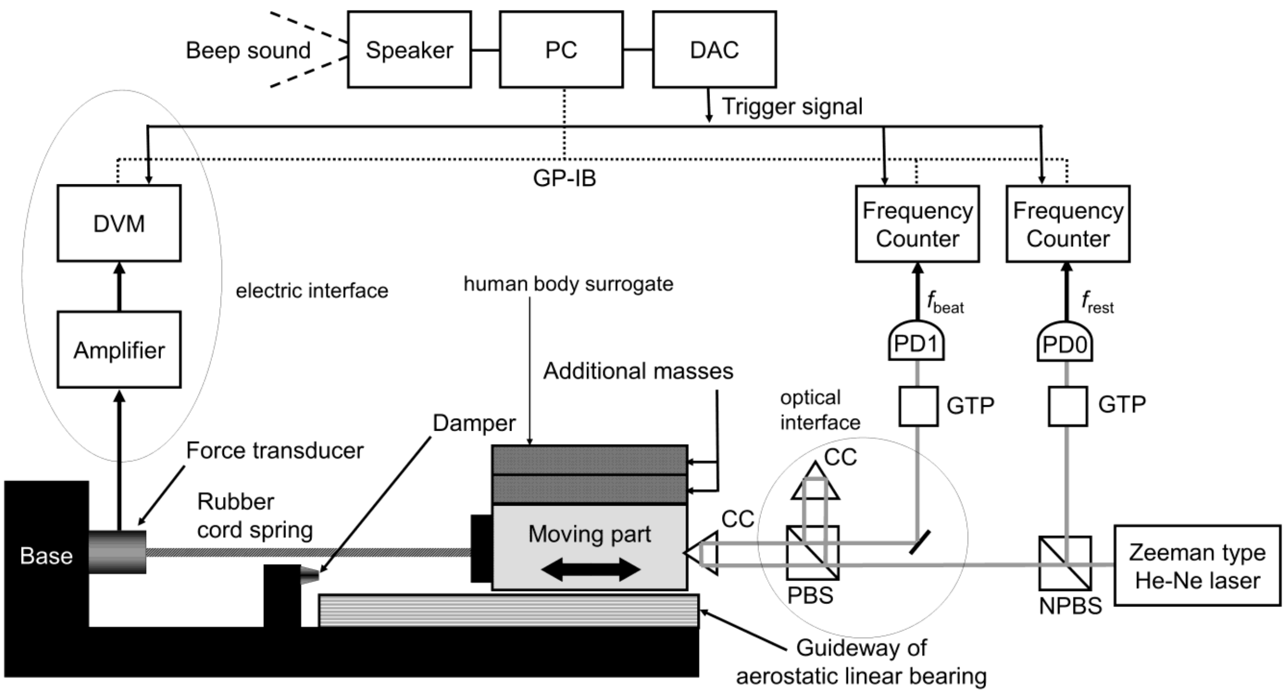

Figure 1. Experimental setup.
Code: CC= cube corner prism, PBS= polarizing beam splitter, NPBS= non-polarizing beam splitter, GTP= Glan-Thompson prism, PD= photo diode, DAC= digital-to-analog converter, DVM=digital volt meter, PC= computer.

Orbit model configuration is designed as Fig.4. The absolute reference is the ISS structure. The benefit of this design is that no large frame nor long bar needs to be deployed. Precision is expected from the use of large ISS module space, which enables the subject astronaut to travel a relatively long distance on the laser beam line. To improve handling easiness, active components would reside at the wall side of the system. Bungee cord is a standard item for exercise on ISS, so it is convenient in regard to re-supply.

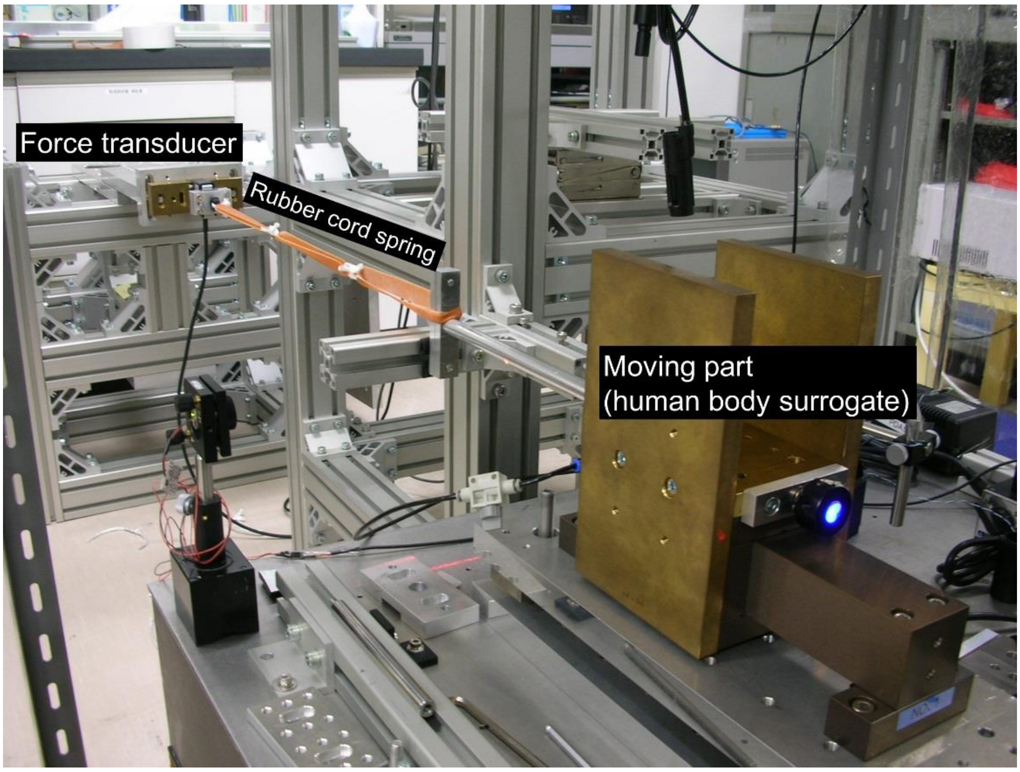

Fig. 2. Photograph of the experimental setup

3.2 Results

The ground model worked and produced mass values as designed. Accuracy was assessed with a simulated body mass of Mcal = 11.628 kg. The spring constant of the bungee cord produced body acceleration of around 1 ms^{-2}. The force value sensed by the transducer is shown in Fig. 3, together with derived measurement value of Mmeas. Mean of Mmeas was 11.5937 kg, which was 0.293 % smaller than the true value.

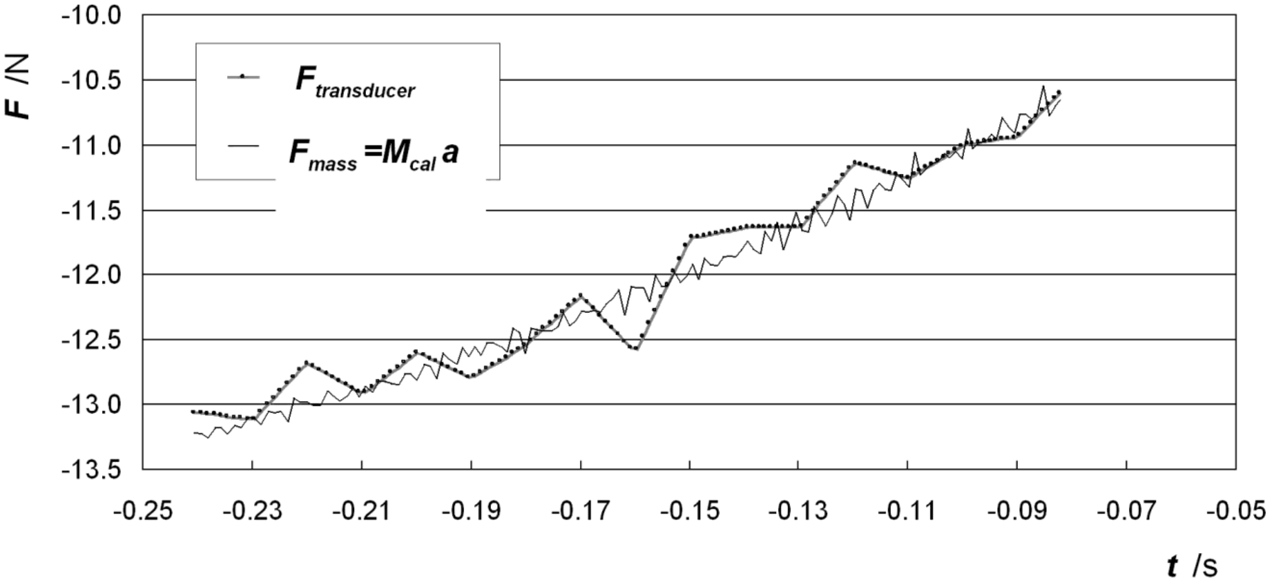

Fig. 3. Force measured using force transducer and optical interferometer

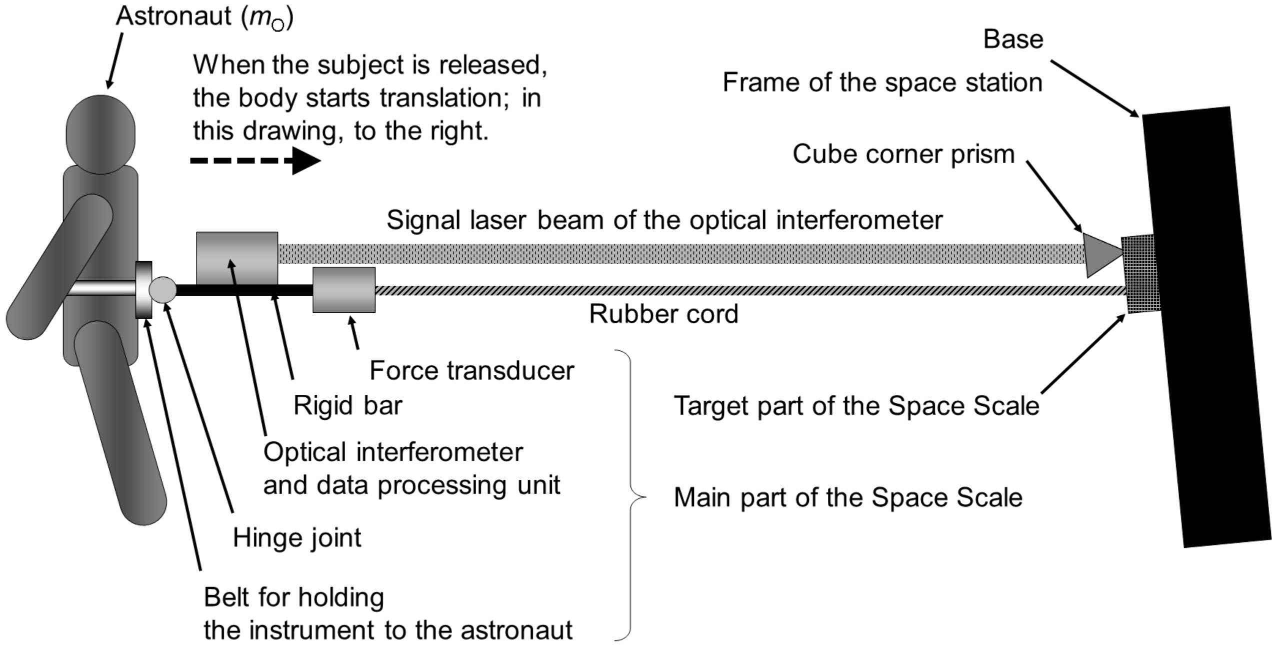

Fig. 4. Space Scale for Astronaut Mass Measurement

4. Ground Model review

The accuracy of the measurement result of M_{meas} was promising for medical use, but not as good as expected. Distance and acceleration measurement by laser interferometry worked as in previous reports [5], as verified by smooth data trend plotted against body displacement. The force values in Fig. 3 show fluctuation. The force sensor output curve against time in Fig. 3 was not smooth. It eventually resulted in compromised precision of M_{meas}.

The measurement has shown that performance of the force sensor was not optimal, and it was the reason why the result accuracy was worse than expected. Selection of the force sensor and its mechanical implementation would be the key for Space Scale. Reducing bungee cord spring constant, to use lower acceleration might increase accuracy and precision.

The elasticity and subject reflex in changing body shape affects the accuracy and precision of the body mass measurement. Our prediction is that training would eliminate these factors. This aspect should be tested aboard parabolic flight aircraft. One combination has been examined [6].

5. Prospects for Exploration spacecraft application

If specimens are small, there are good design for microgravity mass measurement [7, 8]. Difficulties become pronounced when we measure human body mass [9]. For the ISS, proposals are made but new instrument implementation has not happened so far [10].

For the exploration space missions, however, the requirements should be different from that for the ISS. In manned capsule spacecraft, with a small habitable module, apparatus volume and easiness of operations are of utmost importance, while accuracy of measurement can be lower. The range of uncertainty obtained in this paper is adequate for capsule use; robustness of hardware should be well considered for the application. Other body mass measurement device designs are hard to fultill this confined cabin requirements; 'Space Scale' design can be easily applied for a small hardware with easy, shorter time operation.

6. Conclusion

Our new astronaut body mass measurement device 'Space Scale' concept was verified with model measurements. Its uncertainty was moderate, which suggested more developments for the ISS use.

To apply the same design concept to 'exploration' smaller spacecraft is reasonable with 'Space Scale', while other body mass measurement device schemes are difficult to modify and apply.

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