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(NASA-CR-197198) PROPOSAL FOR AN ASTRONAUT MASS MEASUREMENT DEVICE FOR THE SPACE SHUTTLE (USRA) 50 p

Proposal for an Astronaut Mass Measurement Device for the Space Shuttle

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For medical reasons, astronauts in space need to have their mass measured. Currently, this measurement is performed using a mass-spring system. The current system is large, inaccurate, and uncomfortable for the astronauts. NASA is looking for new, different, and preferably better ways to perform this measurement process. After careful analysis our design team decided on a linear acceleration process. Within the process, four possible concept variants are put forth. Among these four variants, one is suggested over the others.

The variant sugges~~ted is~~ that of a motor-winch system to linearly accelerate the astronaut. From acceleration and force measurements of the process combined Newton's second law, the mass of an astronaut can be calculated.

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Background and Statement of Problem

Weighing oneself is a daily activity for many people. Many simple devices have been constructed to measure the earth's gravitational pull on the human body. These devices are commonly known as scales.

The act of weighing oneself may only take a few seconds, and the procedure is as simple as a half step up onto the scale. However, the problem examined in this project is when the earth no longer pulls on the body. Measuring the mass of a human suddenly becomes much more complicated under these circumstances.

NASA has this problem with the astronauts aboard the space shuttle. Although the astronauts are only in space for a few days at a time, this duration can be long enough for the drastic physiological effects of weightlessness to develop. Astronauts lose fluids while in microgravity. The fluid in the body travels from the legs and lower abdomen to the area around the heart and head [NASA, 1988]. This condition is not normal for the human body, and the body perceives the problem as too much fluid in the body, rather than a shifting of fluid due to an absence of gravity.

As a consequence, fluids are rejected by the body and the astronaut can rapidly lose weight. The body also does not have to support itself in a microgravity state. The body is not continually working against gravity as it is on the earth's surface. The body takes on a natural posture. These factors cause the muscles to atrophy. This deterioration adds to the weight loss of an astronaut.

Due to this weight loss, a way to measure the effect of weightlessness on the body is to monitor the astronaut's mass. This process of weighing the astronaut seems ordinary and commonplace, but without gravity the measurement becomes impossible by ordinary means. The absence of gravity also allows body fluids to move more freely within the body than usual. The movement of these fluids in the body caused by its ullage can create unwanted oscillations during the body's motion. Therefore, any measurement that requires the astronaut to be set in motion must consider the astronaut's ullage. The astronaut's body can be modeled by a double mass spring-damper system.

At present, NASA uses a spring-mass system to measure the astronaut's mass. The mass of the system is the astronaut, and springs are used to find the resonant frequency of the system. From the resonant frequency the mass can be calculated. NASA would like to correct many of the disadvantages of their current mass measurement system. The mass-spring system NASA now uses is large and bulky. NASA would like a smaller, lighter system to measure the astronaut's mass. The mass-spring system requires the astronaut to maintain a fetal position during the measurement process in order to closely replicate a point mass. This position is uncomfortable for the astronauts, and a process that is easier on the human body is preferred. Finally, the mass-spring system does not have the accuracy that NASA needs.

Before setting out to solve NASA's problem, our design team felt a need to clarify the task at hand. The team reviewed the problem statement submitted by the customer, searching for any inherent bias or ambiguity in the statement. Few problems were found. The initial statement was clear and straightforward. One bias that was identified was that the statement maintains that the astronaut must be accelerated. However, several possibilities of performing a mass measurement (i.e., conservation of momentum, p=mv) come to mind that do not require the body's acceleration. Other than this bias, the problem statement was clear to our design team.

A concise statement of the problem was arrived at by the design team to give the team direction in solving the problem. The problem statement was given as follows:

Design an astronaut mass measurement device that is comfortable, accurate, and accounts for ullage effects.
From here, the team was prepared to begin work on a specification sheet.

Scope and Limitations

There are various human physiological responses to weightlessness that affect the health of the astronauts. Astronauts lose blood volume, bone density, and muscle mass during weightlessness. As a result of these effects, medical personnel need to monitor body mass to help assess the astronauts' physical condition. This will require a device that can measure the astronauts mass in space. This poses a very difficult problem due to the absence of gravity. Another difficulty is the complications caused by the ullage effect.

The main design issue is determining a method for measuring mass without gravity while accounting for the ullage effect. The ullage effect is a shift of internal body fluids and soft tissue as a transient response to body acceleration. If the body was accelerated to determine mass, this effect would need to be accounted for accurately. A model for the human body has been constructed to account for the "body fluid sloshing" of the ullage effect during calculations. The model consists of two lumped masses which are 80% and 20% of the total body mass respectively. The two masses are connected by spring/dashpot assembly in parallel. The resulting system has an undamped natural frequency of 2 Hz, with a damping coefficient of 0.5.

Some of the other important design issues for the mass measurement system are accuracy, comfort, size requirements. The device must be able to account for any ullage effects and give an accurate mass measurement with a resolution of 0.1 pounds. The device must also be comfortable for the astronaut. To account for comfort, the body position, the time in the device, and any forces or accelerations applied will need to be considered. The customer has placed a limit upon device mass, and there are significant constraints on size. These include limits on space allowed for movement of the astronaut and on stowage volume.

Device Specifications

The design team has generated a list of specifications (Table 1) to serve as a set of guidelines during the design process. Following the specification sheet is a discussion of important specifications.

Quantification of Customer Requests. Most of the customer's desired device attributes (mass, accuracy, range, etc.) were quantified in the preliminary specification sheet provided by the customer. Astronaut comfort, however, required, further development.

We describe comfort as a function of the astronaut's position, the amount of time the astronaut must assume this position, and the acceleration to which the astronaut is subject. Elaboration on each these can be found in the discussion of ergonomics.

Table 1: Device specifications

Date of Change	D W	MASS MEASUREMENT DEVICE SPECIFICATIONS Requirements	Resp	Verifications
		Function		
	D	Allow determination of an astronaut's mass while on the Space Shuttle (CR)		
	D	Operate in the pressurized portion of the Space Shuttle (CR)		
	D	Resolution of 0.045 kg (i.e. +/- 0.023 kg) (CR)		
	D	Accuracy of device not affected by the ullage effect (CR)		uncert. anal.
		Kinematics		
	D	Allow quick set-up and take-down (<2 hour) (CR)		
	D	Allow rapid removal of an astronaut from the device (< .17 hour) (CR)		prot. test
	D	No tools required for assembly, disassembly, maintenance, or use (CR)		prot. test
		Ergonomics		
	D	Comfortable for the astronauts to use (CR)		
	D	Acceleration: x: -2.5g to +2.5g (DR) y: minimize (DR) z: -1g to +2g (DR)		analyt. calc.
	D	Revolution: No more than 6 rpm about any axis through the body (DR)		
		Time:		
	W	Minimize the time that the astronaut is secured in device (DR)		
	D	The astronaut should spend no more than 5 minutes secured in the device (DR)		
	D	Must fit a wide range of astronauts; from 5th percentile woman to 95th percentile man (See NASA Std 3000/vol 1/rev A sec 3) (CR)		
		Operations		
	D	Controls and displays meet NASA Std. 3000/vol 1/rev A sec 9 (DR)		
	D	Digital readout of mass provided on instrument (CR)		
	D	Maximum number of crew persons needed to make measurement: two (one assistant and one person being measured) (CR)		
	D	Use standard signals specified in sec 12 (DR)		
		Geometry		
	D	Stowage volume less than or equal to .057 m^3 (CR)		
	D	Maximum pulling or rotational distance allowed = .914m (CR)		
	D	Maximum mass 6.8 kg (CR)		
	D	Fits standard mechanical and electrical lab connections (see sec 11) (DR)		
	D	Entire system fits into two stowage lockers (.51 x .43 x .05 m each) (DR)		
		Environmental Conditions		
	D	Temperature 292 - 300K (DR)		
	D	Pressure 101.3 kPa (DR)		
	D	Withstand lift off acceleration of 3g (DR)		
		Maintenance and Production		
	D	Life span of 10 years (DR)		fatigue anal.
	D	Design to fit NASA maintenance stds in sec 12 (DR)		
	D	Need at least one back-up or redundant system (DR)		
	D	Use standard parts and processes (DR)		
		Energy		
	D	Battery powered, battery lifetime before recharge: 3 hours (CR)		
	D	Available power is Xamps at Xvoltage (DR)		

Operations. Digital readout and number of crew members required for operation were specified by the customer. The design team has specified the use of standard input/output devices as described in section 12 of NASA Standards 3000/vol I rev A/Sec 9. This section discusses such considerations as the advantages and disadvantages of different types of switches and I/O devices. Also addressed are display considerations such as readability, glare, and luminescence. There are additional constraints for device controls and displays described in NASA Standards Section 9.

Geometry. Stowage volume (0.057 m^3) was specified by the customer. Comparing this to the size of available stowage lockers shows that the device components must fit in two of these lockers. Dimensions of the lockers (0.51 x 0.43 x 0.05 m ea.) must be considered during device design.

The device will be used in the lab module which can be installed in the space shuttle cargo bay. The module contains standard electrical connections for device power, as well as mechanical connections for anchoring the device. These connections are described in NASA Standards 3000/vol I/rev A/Sec 11. This section discusses connector selection, identification, alignment, spacing, and accessibility.

Ergonomics. The ergonomic customer and design requirements are important to the overall design of the mass measurement device. The customer requires that the device be comfortable for the astronauts to use [Bourell, 1994]. This general restraint can be quantified in more detail to give some better design guidelines. The device must be designed to fit the user population without causing discomfort or physical exhaustion. The device should be safe and it must not subject the astronauts being measured to any stressful movements.

The device must be designed to fit a wide variety of astronauts ranging from the 95th percentile man to the 5th percentile woman. The device can be designed three different ways to fit users with such a wide size variety: one size fits all, an adjustable restraint system, or the device can have different sizes for different user size ranges. Since the device will be used in a 0-g environment, it must be able to secure the astronaut being measured in a natural 0-g position. Unnatural body postures which must be maintained for extended periods of time may result in fatigue problems.

Due to the absence of gravity, the mass measurement device might need to accelerate or displace the astronaut being measured to obtain a mass measurement. The accelerations that the astronaut is subjected to must be safe and reasonably comfortable. The restrictions on linear acceleration depend on the magnitude, direction, and duration of the force being applied, the rate of onset and decline of the applied force, the body positioning and fluid shift, and the extent of microgravity adaptation. Table 2 gives the limitations of linear acceleration.

Table 2: Limits on linear acceleration.

Linear Acceleration Limits		
Direction	Magnitude	Effects on Astronaut
Positive x	4	Tolerable up to 1 hour
Negative x	minimal	Should be minimized due to pain and discomfort
Positive Z	2.5	Difficulty in moving
Negative Z	1	Unpleasant but tolerable
Y	minimal	Should be minimized to avoid head and neck injuries

There are also restrictions for the rotational acceleration and fatigue that astronauts can withstand. Most subjects without prior experience can tolerate rotation rates up to 6 RPM in any axis or combination of axis [NASA, 1988]. The operation of the measuring device will require some physical exertion from the astronauts. Any tasks that might be required of them should not be too strenuous. The tasks could be performed by any of the crew members, therefore the metabolic energy requirements of the tasks should be kept 10 to 20% lower than what would be considered tolerable by the least fit of the users [NASA, 1988]. This will insure that the operation of the device will not tire the astronauts by requiring too much physical exertion.

The measurement device must be designed with consideration for the safety of the users. Two of the primary considerations for crew safety are system failures and design induced crew errors [NASA, 1988]. Both types of errors can cause injury to the crew and the measurement system. There are numerous safety standards concerning safety design, mechanical and electrical hazards, guards, warnings, fire protection, etc. that are very important for the safety design of the measurement device.

Maintenance and Production. Maintenance is a very important design issue during the design of the mass measurement device. There are many factors that need to be considered when designing for maintainability. Preventative maintenance should be minimized and require as little crew time as feasible. If maintenance requires that system operations be interrupted, redundant systems should be considered. The time, skill level requirements, and training for maintenance operations should be minimized as much as possible. Any required alignment, calibration, or adjustment should be easily and accurately accomplished [NASA, 1988]. There should be automatic fault detection and isolation whenever possible.

Modularity, compatibility, and cost need to be considered during the production design process of the mass measurement system. The system and its components need to be modular in design by having interchangeable and common parts with other mission systems. For example, if every screw in the space shuttle was a Philips screw then if possible use Philips instead of flat screws for the design. The mass system should also be compatible with existing space shuttle electrical and mechanical connections. It should also be compatible with all space shuttle equipment i.e., it should not interfere with the operation of measurement of any of the space shuttle systems. The cost of materials, parts, and required manufacturing processes should be considered when designing all of the components of the mass measurement device. Use common parts and manufacturing procedures whenever possible.

Power. The mass measurement device will be required to operate from a battery with voltage and amperage to be given by the customer at a future time. The battery lifetime is three hours before recharging and its total available power is to be determined later by NASA. This will be the only available power source other than the physical power from the astronauts using the device. The weight of the battery has not been given, but needs to be included in the total weight constraint of 66.7 N.

A long system life should be possible by designing for maintainability. The mass measurement system will only be used a few times a day during space shuttle missions. The space shuttle missions take up only about 6 months out of the year. Because of the short total duration of most space shuttle missions and the scattered use of the mass measurement system, a life span of about 10 years should be expected.

Process Alternatives

Due to the absence of gravity, conventional methods of mass measurement (i.e., the traditional scale) will be inapplicable. We thought of six possible processes that could be used to measure the mass of an astronaut: electrical, angular momentum, angular acceleration, linear momentum, linear acceleration, and calculation from density and volume measurements. To focus our design efficiently, we felt it necessary to eliminate some of the possible mass measurement processes. After some research, five of the six processes were eliminated. The linear acceleration process scored highest in our decision matrix. The advantages and disadvantages of each process are described below. Figure 1 presents the morphological matrix.

Electrical. The electrical process included two types of electrical measurement to determine the mass: inductive and capacitive. The inductive process contains a large inductive coil which is connected to a resonant circuit. The astronaut is placed within the coil and the resonant frequency is changed by the presence of the body. The resonant frequency changes could be calibrated for different masses. If the calibration curve was a monatonic function, then a mass could be calculated for a change in the circuit resonant frequency [Cogdell, 1994]. This idea was abandoned because the magnetic properties of the human body are so poor that small mass differences could not be detected due to the lack of sensitivity of the circuit. For example, the change in resonant frequency caused by inducting a 50 kg or a 200 kg body would be about the same [Pearce, 1994]. The strong inductive coil could also interfere with the some of the space shuttle equipment due to the strong magnetic fields it emits.

The second type of electrical mass measurement process is a capacitive system. Since the human body is mostly fluid, it has very strong electrostatic properties. The capacitance between two plates would change dramatically if a body was placed between them. The change could be measured by a resonant circuit similar two the one in the inductive system. The change in resonant frequency could be proportional to the mass of the astronaut placed between the plates. Unfortunately, capacitance is a strong function of the area between the plates. This means that the system would be more sensitive to the astronaut's area than to his mass. The large capacitive plates could also generate strong static charges that might interfere with other equipment.

Linear Momentum. In the linear momentum process, we use the conservation of linear momentum to find the astronaut's mass. The astronaut is secured to a support and moves at a constant velocity until he or she hits a second mass. The velocity of the astronaut before impact and the velocities of the astronaut and second mass after impact are recorded. Knowing these values and the value of the second mass, we use the conservation of momentum to find the mass of the astronaut. The velocities are assumed to be constant enough over a time period needed to read the speedometers. Figure 2 shows how this would be done.

Process Morphological Matrix

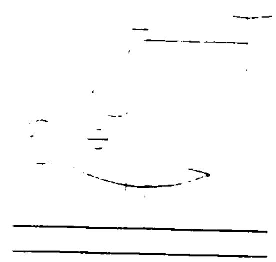
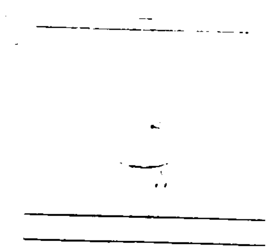
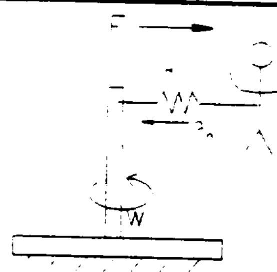
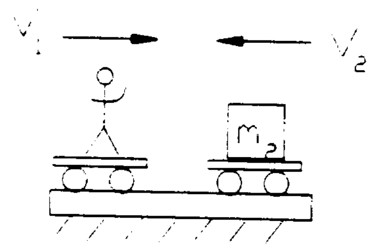
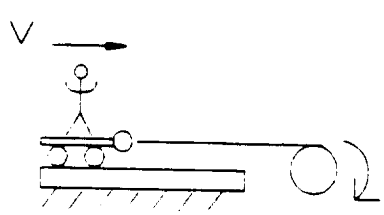
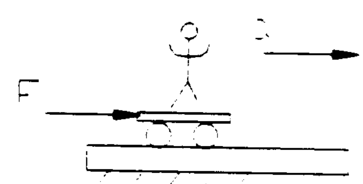
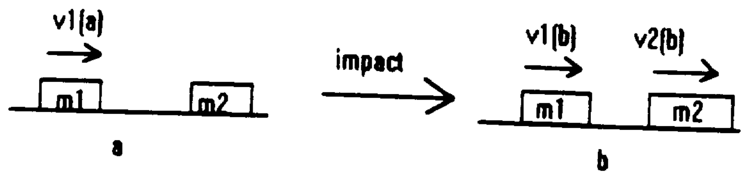
Type of Motion / Equations	Process #1	Process #2
$m_1 v_1 \omega_1 = m_2 v_2 \omega_2$ Angular Momentum	 Impact Astronaut (Pendulum)	 Rotate Astronaut (Rotation)
$a_n = m\omega^2 r$ Angular Acceleration	 Rotating Astronaut	
$\sum m_1 v_1 = \sum m_2 v_2$ Linear Momentum	 Impacting Carts	
$F = ma$ Linear Acceleration	 Pull Astronaut	 Push Astronaut

Figure 1: Process Morphological Matrix

This could work were it not for the ullage effect. When the astronaut impacts the second mass, it causes oscillation of the mass-spring-damper system that models the ullage phenomenon. This oscillation would make calculations complicated, and impair accuracy. This process does not meet any of the decision criteria well and is not a feasible option for moving the astronaut.



m1 = astronaut

m2 = known mass

v1(a), v1(b), v2(b) measured directly with speedometers

Conservation of momentum: $m1v1(a) = m1v1(b) + m2v2(b)$

Solve for m1

Figure 2: Conservation of linear momentum.

Angular Momentum. One possibility for mass measurement is to analyze the law of the conservation of angular momentum. The idea of the team is to spin the astronaut at a constant angular velocity and then change one parameter of the equation 'G = rmw,' where 'G' is angular momentum, 'r' is the radius to the center of mass, 'm' is the mass of the rotating object, and ω is the angular velocity. Once one parameter of the right hand side is changed then (observing the law of conservation of angular momentum) the mass can be calculated given that the other variables on the right hand side are measured or are known.

The team felt that changing ω would be difficult. Instead, angular velocity would be one of the variables easiest to measure for response to a forced change. This elimination left us with the two remaining possibilities of changing the mass or the radius.

To change the mass the team thought that possibly an astronaut could be rotated about an axis to impact a second, known mass. The change in the astronaut's rpm could provide enough data to calculate the mass.

To change the radius the team had a number of ideas. The first involved the spinning of a lone astronaut around an axis at a fixed radius. A release mechanism could then move the astronaut back to a larger radius. Once again, the rpm change can be measured and the mass calculated. A second idea involved spinning the astronaut, but this time opposite a counterweight that would change its radius rather than the astronaut's.

The collision involved with the changing mass idea has negative ullage effects. A collision causes the body fluids to oscillate in the body. These oscillations affect the accuracy of the measurement. Additionally, the weight to be collided with would severely cut into the 15 pound maximum weight constraint. Even at 15 pounds, the best this amount can change the rpm in the limited sphere of motion is 17 percent. We want the greatest change possible so that an accurate measurement can be taken.

The idea of changing radius has a number of problems. This concept also runs into problems with ullage. A sharp force is required to move the astronaut as swiftly as possible to the new radius. This swiftness is needed to eliminate momentum losses during the transition. A swift movement due to a sharp force can also set body fluids in motion. The fluid's oscillations are damped. This damping dissipates energy and destroys the law of conservation of angular momentum at its foundation. The counterweight idea solves the ullage problem but brings in new obstacles of its own. Once again, the weight would need to be less than 15 pounds which does not afford much sensitivity to measurements. The team inquired whether an already present source of weight on the shuttle could be used. It was suggested that we do not rely on such a possibility [Norrell, 1994]. An answer to this is to use an additional astronaut as a counterweight. Performing the test three times with three different astronauts alternating places gives the needed information. However, assuming that one astronaut would perform the measurements while two astronauts are in the apparatus, this solution violates the constraint that no more than two astronauts can be occupied by the measurement process at any given time.

In addition to the aforementioned, a singular problem exists with any type of angular process in which the radius needs to be known. The radius to the center of the astronaut's mass must be measured. The center of mass from head to toe or from chest to back is not easily determined due to the asymmetric nature of the human body. Variation in body type also make these directions difficult to work with. Using the direction of left to right on the astronaut's body is more practical if the tip of the nose is considered near the axis. However, even if this direction is used, once the body begins spinning, the fluids inside the body will radially migrate, and the center of mass will change. Note that if there were less of a constraint on the allowable sphere of motion, such discrepancies in the measurement of the radius might become insignificant.

Angular Acceleration. Angular acceleration measurement is difficult because it involves taking the resultant of two acceleration components. An object that experiences angular acceleration will have a normal and tangential component of acceleration. In Figure 3 below, a_n = normal acceleration, a_t = tangential acceleration, and a = total angular acceleration.

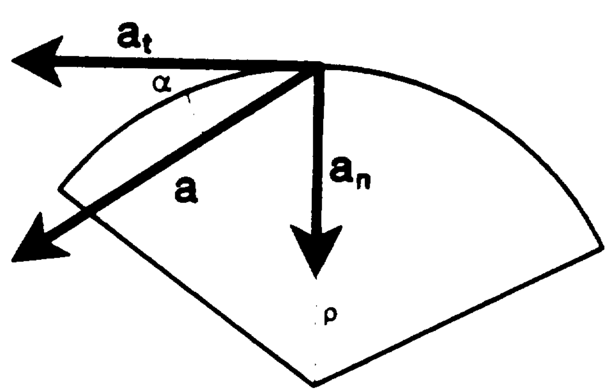


Figure 3: Acceleration vectors in angular acceleration.

The equations for this type of acceleration are as follows:

$$a_t = \frac{\Delta V}{\Delta t} \qquad a_n = \frac{V^2}{\rho}$$

$$\tan\alpha = \frac{a_n}{a_t} \qquad a = \frac{a_n}{\sin\alpha}$$

where V = velocity,
t = time, and
ρ = radius of curvature.

It would be easier to spin an object at a constant angular velocity and measure only its radial or normal acceleration. The velocity could be determined by knowing the speed of a motor. A force transducer, such as a spring, could measure the force. The force would be :

$$F = ma \Longrightarrow F = \frac{mV^2}{\rho}.$$

The only problem with this is finding an accurate measure of the radius of curvature, which is the distance from the rotating axis to the center of mass of the astronaut. Measuring the center of mass of an astronaut would be complicated since the center of mass varies for each astronaut and the ullage effect may cause the center of mass to shift when the astronaut is accelerated. Therefore, the angular acceleration and radial acceleration methods of measuring the mass of an astronaut are not feasible [Meriam, 1986].

Linear Acceleration. One process choice the design team considered used the relationship between a constant force applied to the mass and its resultant linear acceleration:

$$F = ma$$

Upon application of a known force, the acceleration can be measured, allowing calculation of the astronaut's mass. This method has numerous advantages. Only one mathematical relationship is involved, and only two quantities need to be measured, so inaccuracy is reduced. Additionally, force (or pressure) and acceleration are measurable using devices which are already commonly used. As motion will be linear, device complexity can be minimized.

Possible disadvantages of this method include the difficulty in applying an invariant force. This might be overcome by the use of an automated measurement system which samples instantaneous force and acceleration several times each second. A data inquisition program could then receive the information and calculate the mass.

Another obstacle is presented by the customer's accuracy demands. A resolution of approximately 0.00043% has been specified [Norrell, 1994]. This will require a very small full-scale uncertainty in the measurement devices. The applied force will also have to be kept below that which would amplify the ullage effect.

Determination of Mass from Density and Volume. The design team considered determining mass from astronaut volume and average density. Ideally, we hoped to use technology similar to that used in hospital CAT (Computer Aided Tomography) scans for calculation of astronaut volume and density.

CAT systems are too massive to be used aboard the shuttle, but there are methods of tomography which do not require prohibitively massive equipment. Applied potential tomography (APT) is used to monitor the shift of bodily fluids into the upper body during weightlessness [Barber, 1991]. Electrodes are placed along the length of the astronaut's body, on both front and back. The impedance between each electrode pair is obtained by sending a current through the subject's body between each pair. This impedance gives an indication of the fluid present at various locations along the body. By comparing measurements made under normal and zero-gravity conditions, the shift of fluid is quantified. A simple diagram of the system is shown in Figure 4.

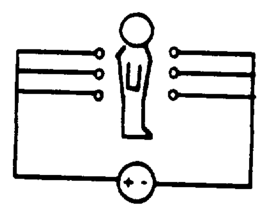


Figure 4: Applied potential tomography set-up. Electrodes are placed along entire body length.

The apparatus necessary for this process has a mass of approximately 5 kg, so mass is not a problem. However, the process only examines a line through the body, rather than a plane, as in a CAT scan. Assuming we could obtain a plot of a plane through the body, to obtain the accuracy requested by the customer we would need to examine thousands of planes. There would also have to be very little distance between planes.

We cannot obtain the density and volume information necessary for mass calculation with APT. However, the technology merits future consideration. If the tomography capabilities of CAT systems can be combined with the portability of APT systems, the result might be a very accurate mass measurement method.

Process Selection. In order to eliminate some of our process choices we constructed a decision matrix. We chose different important criteria for our grading and gave weights that corresponded to their importance, e.g., accuracy (0.5) is more important than complexity (0.2). The total weight of the tree is one, and each criterion makes up a portion of the total, all criteria summing to one. Figure 5 shows the weighting tree for the decision matrix. For this preliminary decision matrix, we decided that accuracy, ullage effects, and complexity were the main design issues that should be addressed. Accuracy represents the overall accuracy of the entire process and it carries the most weight. Ullage effects are next in importance and they represent the possible problems with the ullage effects interfering with measurement. The last decision criterion is complexity and this represents the overall difficulty, number of steps, and moving parts required for each measurement process. In the process decision matrix (Table 3) it is obvious that the linear acceleration process wins by a large margin. We will eliminate all of the other possible mass measurement processes and continue our design with the linear acceleration systems.

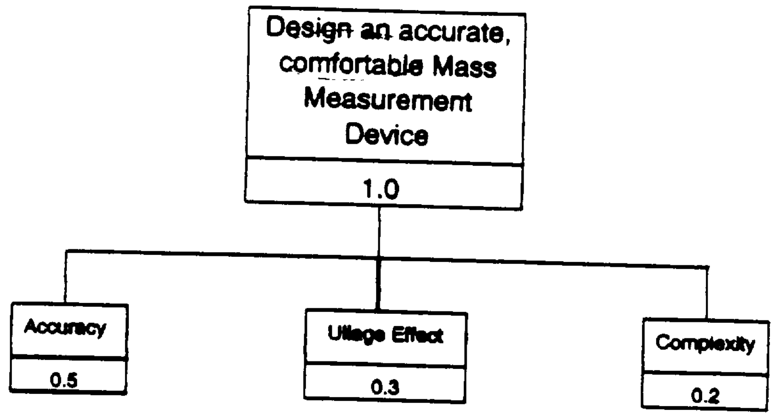


Figure 5. Process Decision Matrix Weighting Tree

Table 3: Process Decision Matrix

PROCESS DECISION MATRIX				
Spec / Concept / Weight	Accuracy	Ullage Effects	Complexity	Total
	0.5	0.3	0.2	1
Angular Momentum (Impact)	60 / 30	40 / 12	90 / 18	60
Angular Momentum (Rotation)	65 / 32.5	55 / 16.5	80 / 16	65
Angular Acceleration	70 / 35	90 / 27	85 / 17	79
Linear Momentum	70 / 35	40 / 12	90 / 18	65
Linear Acceleration (Push)	95 / 47.5	85 / 25.5	95 / 19	92
Linear Acceleration (Pull)	95 / 47.5	85 / 25.5	95 / 19	92

Simulation of Linear Acceleration of Astronaut

To determine the feasibility of our process choice, linear acceleration, we simulated the response of the body of the astronaut to a linear acceleration. We wanted to get a rough idea of the magnitude of the force needed, the resulting acceleration, the effect of the ullage maneuver, the power required, and the time available for force and acceleration measurement. Simulation was done with the use of the model supplied by the customer in the problem statement. The model consisted of two lumped masses. One mass represented twenty percent of the astronaut's total mass 'm,' the other eighty percent. Connecting the two masses were a spring and dashpot in parallel. The model is pictured in Figure 6.

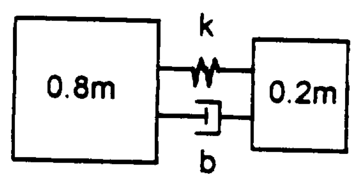


Figure 6: Idealized model of human body.

The customer described the system as having an undamped natural frequency 'f_n' of two Hertz, (or 'ω_n' of 12.5 radians/sec) and a damping coefficient 'ζ' of 0.5. Using this information, we derived spring stiffness 'k' and dashpot damping effect 'b' as functions of the astronaut's mass:

$$k = 157.9m \text{ (m/s)}$$

$$b = 12.57m \text{ (Ns/m)}.$$

Deriving the equations of motion for the astronaut's body was the next step. The 0.2m mass was assumed to represent the parts of the astronaut's body which prevented description of the body as a single rigid mass. These included the legs, body fluids, and any other tissue which may move relative to the accelerating support. We assumed the force would be applied then to the larger 0.8m mass. From a free body diagram, we obtained the equations of motion:

$$0.8mx_1'' + bx_1' - bx_2' + kx_1 - kx_2 = F$$

$$0.2mx_2'' + bx_2' - bx_1' + kx_2 - kx_1 = 0$$

where x_n'', x_n', and x_n represent acceleration, velocity, and displacement, respectively for the two masses. N = 1 for the 0.8m mass, and 2 for the 0.2m mass.

Substituting for 'k' and 'b' in terms of 'm,' and converting the equations into four first order equations (see Appendix B), we were able to enter them into MATLAB for analysis. The analysis assumed that the idealized model supplied by the customer was correct, that there was no friction between the astronaut's support and the surface over which it moved, and that the space shuttle itself was not accelerating the astronaut. Additionally, we assumed there would be negligible movement of the shuttle resulting from conservation of momentum during astronaut acceleration. This seemed a reasonable assumption, as the force we expected to apply was on the order of 10 N.

Using MATLAB, we obtained plots of displacement and velocity versus time for 40, 70, and 104 kg astronauts (these were the approximate minimum, mean, and maximum astronaut masses to be measured). We were looking for the development of a constant acceleration of the two masses. Additionally, we wanted to see if this acceleration would develop (i.e., the ullage effect would damp out) before the astronaut moved the maximum displacement of 0.9144 m.

Examining the velocity plots (Appendix A), we saw that, for each of the three test masses, the 0.8m and 0.2m masses each developed a constant acceleration (indicated by the constant, positive slope of the velocity curve) within one second of application of the force. This would give sufficient time for measurement, as in each case the displacement did not reach 0.9144 m until at least 3.5 seconds after application of the force.

To get an idea of the power requirements, we assumed that we would apply the 5 N force along the 0.9144 distance for a minimum time of 3.5 seconds. This gives an approximate power of 1.3 W. This is probably less than what will actually be required because it does not account for motor inefficiency, friction losses between the movable surface and its support, and the weight of the movable surface.

Next we had to consider the acceleration to which the astronaut would be subject when bringing him to a stop. This did not require computer analysis, but merely application of basic linear motion equations. We assumed the astronaut was subject to the same 5 N force as in the computer analysis, and that all necessary measurements could be taken before the subject moves 0.7 m. This left 0.2144 m in which to stop the subject. This would require that astronauts of 104 kg and 40 kg be subject to decelerations of 0.16 m/s^2 and 0.41 m/s^2, respectively. These accelerations were well below the 2.5g maximum stated in our specifications.

Functional Description

Process Description. The process consists of three parts: preparation, execution, and conclusion, as shown in Table 4.

Table 4: Process description.

Preparation	Execution	Conclusion
Set up device	Activate device	Unload astronaut
Calibrate device	Transform energy	Disassemble and store device
Check safety	Accelerate astronaut	
Check system	Receive signal	
Activate backup system	Transduce signal	
Insert astronaut	Condition signal	
Secure Astronaut	Display reading	
	Deactivate device	

Function Structure. The global function structure, or 'black box,' shows the overall function that needs to be accomplished, which is astronaut mass measurement. Energy flows needed to power the device are the battery power and any human energy that may be necessary to load, secure, and unload the astronaut. Energy flows out of the system will include any losses, such as heat. Material flows in and out of the device will be the astronaut. Signal flows into the device will include an on/off signal and human input, such as decisions to turn the device on or off. The signal flows out are the on/off signal, the mass reading, and system operation/warning signals. Figure 7 shows the device's global function structure.

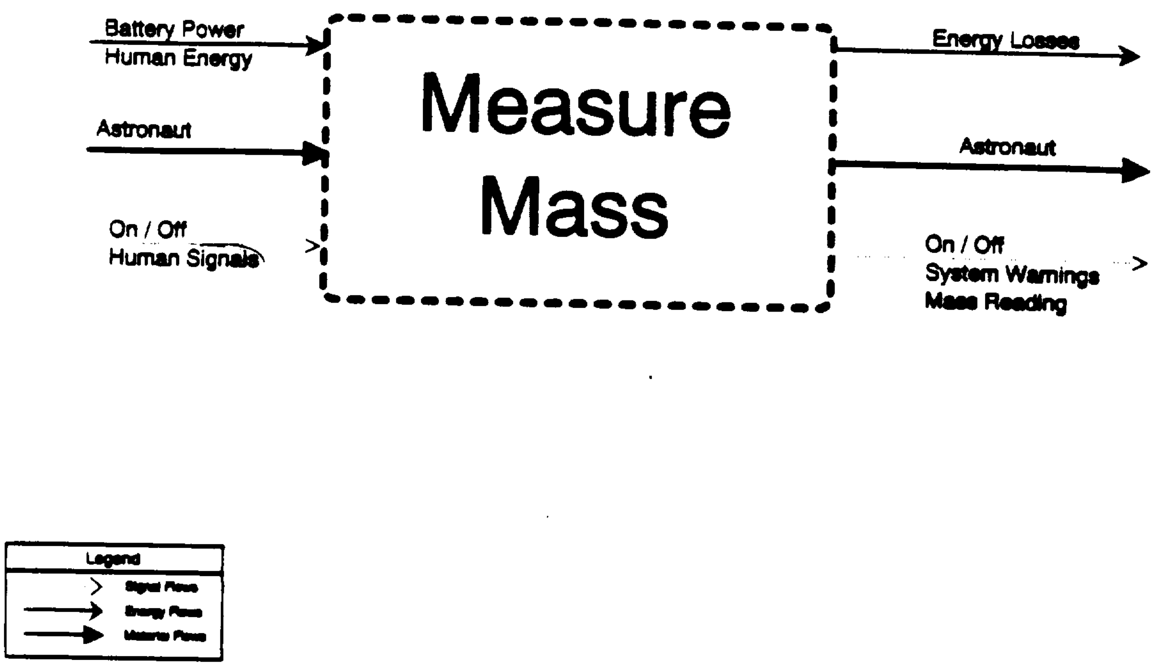


Figure 7: Global function structure

The refined function structure is shown in Figure 8. The boundary of the function structure includes everything the system does from the time it is activated to the time it is deactivated. It does not include the setting up of the device or its disassembly and storage because the device is not doing anything. The boundary does include the human powered functions of inserting, securing and unloading the astronaut, because those functions describe material into and out of the system. The functions shown in the function structure are discussed below.

Activate power. A human signal, such as the press of a button or a spoken command, is needed to tell the device to start. The device draws power from a battery and sends out a signal saying it is activated.

Transform energy. The battery's energy is transformed to useful energy for calibrating, checking the system and safety, moving the astronaut, and measuring the mass.

Calibrate. A human signal is needed again to tell the system to calibrate, and the system returns a signal when it is done.

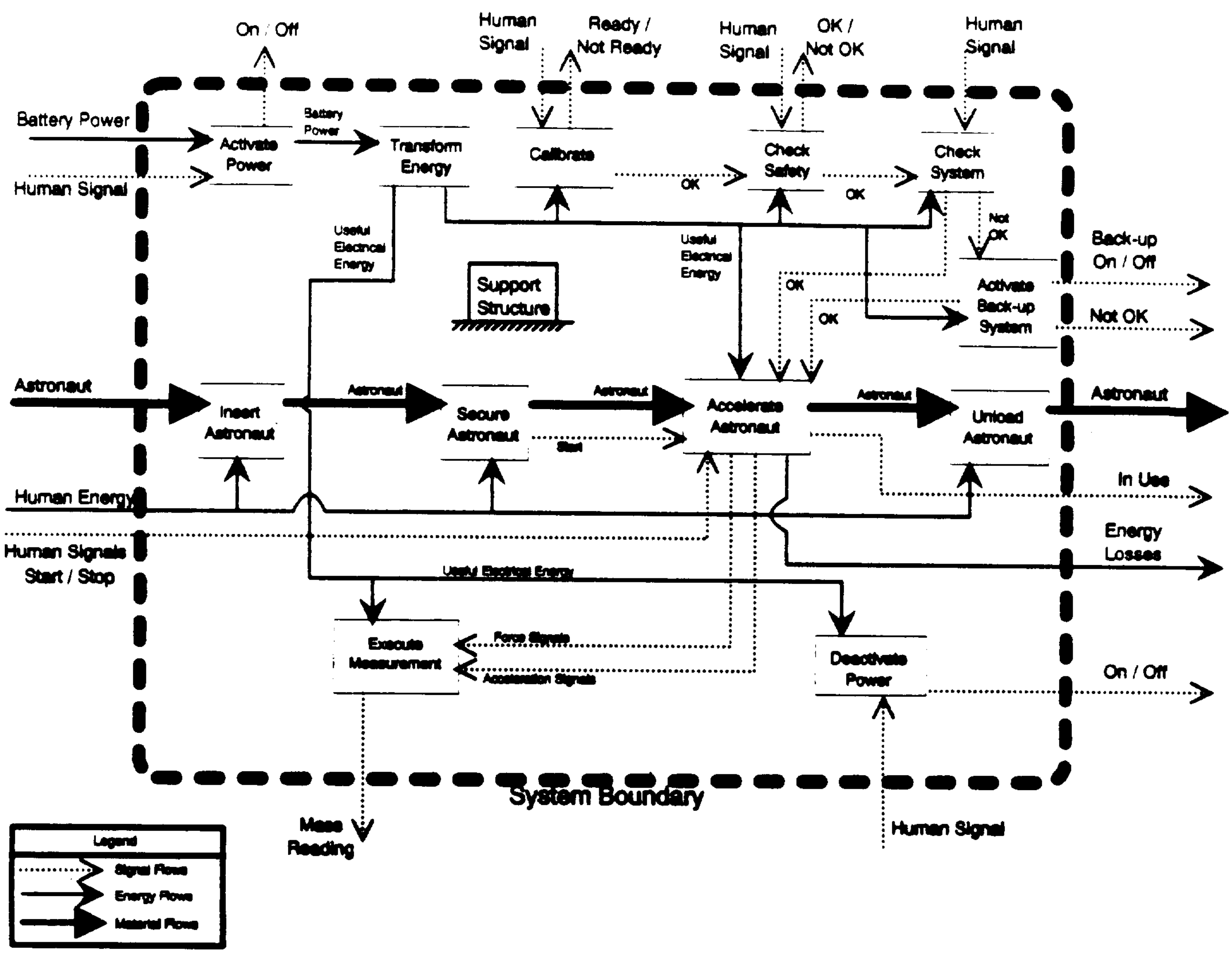


Figure 8: Refined Function Structure

Check safety. The system does a safety check after it is calibrated and after receiving a human signal to start. When the check is finished, it sends a signal back to the operator telling if the device is safe for an astronaut to be placed in it.

Check system. After an astronaut's safety is secured, the system receives a human signal to check itself to see if everything is working properly. If everything works, a measurement can be taken. If everything is not working, a backup system is activated.

Activate backup system. The backup system is only used when the normal system is not working. It sends a signal to the operator when it has been activated, and then measurement can be executed. If it is not working, it sends a signal informing the operator.

Insert astronaut. This requires human energy, probably from the astronaut himself.

Secure astronaut. Human energy is again needed to make sure the astronaut does not move in a way to disturb the mass measurement.

Unload astronaut. Human energy is need to release the astronaut and remove him or her from the device.

Accelerate Astronaut Function Structure. The function 'accelerate astronaut' is further refined in Figure 9.

Transform Energy. Useful electrical energy must be transformed into mechanical energy.

Provide Mechanical Advantage. The mechanical energy is used to develop a constant mechanical force.

Apply Force. When the system is operating properly and the astronaut is ready, a start signal is given. The constant mechanical force is provided to move the astronaut. Kinetic energy is produced and an "in use" signal is given.

Guide Astronaut. The astronaut needs to be guided so that he accelerates in a straight line.

Maintain Force. While the force is being applied, the force and acceleration signals are sent to the measuring devices. Energy is lost from the system due to friction.

Stop Astronaut. When a stop signal is sent into the system, the astronaut will decelerate. Energy will also be lost from the system during the deceleration.

Return to Initial Position. Mechanical energy may be needed to return the moving parts of the device to the initial state. A return signal may be needed to move the system to its initial state. This way the device will be ready for the next astronaut to use.

Execute Measurement Function Structure. The function 'execute measurement' can be further refined in Figure 10.

Receive Acceleration Signals. Useful electrical energy is used to receive the acceleration signals from the acceleration measurement device.

Receive Force Signals. Useful electrical energy allows the force signals to be received from the force measurement device.

Transduce Acceleration Signals. The received acceleration signals may be transduced to another form (i.e., mechanical to electrical).

Transduce Force Signals. The received force signals may be transduced into another form (i.e., mechanical to electrical).

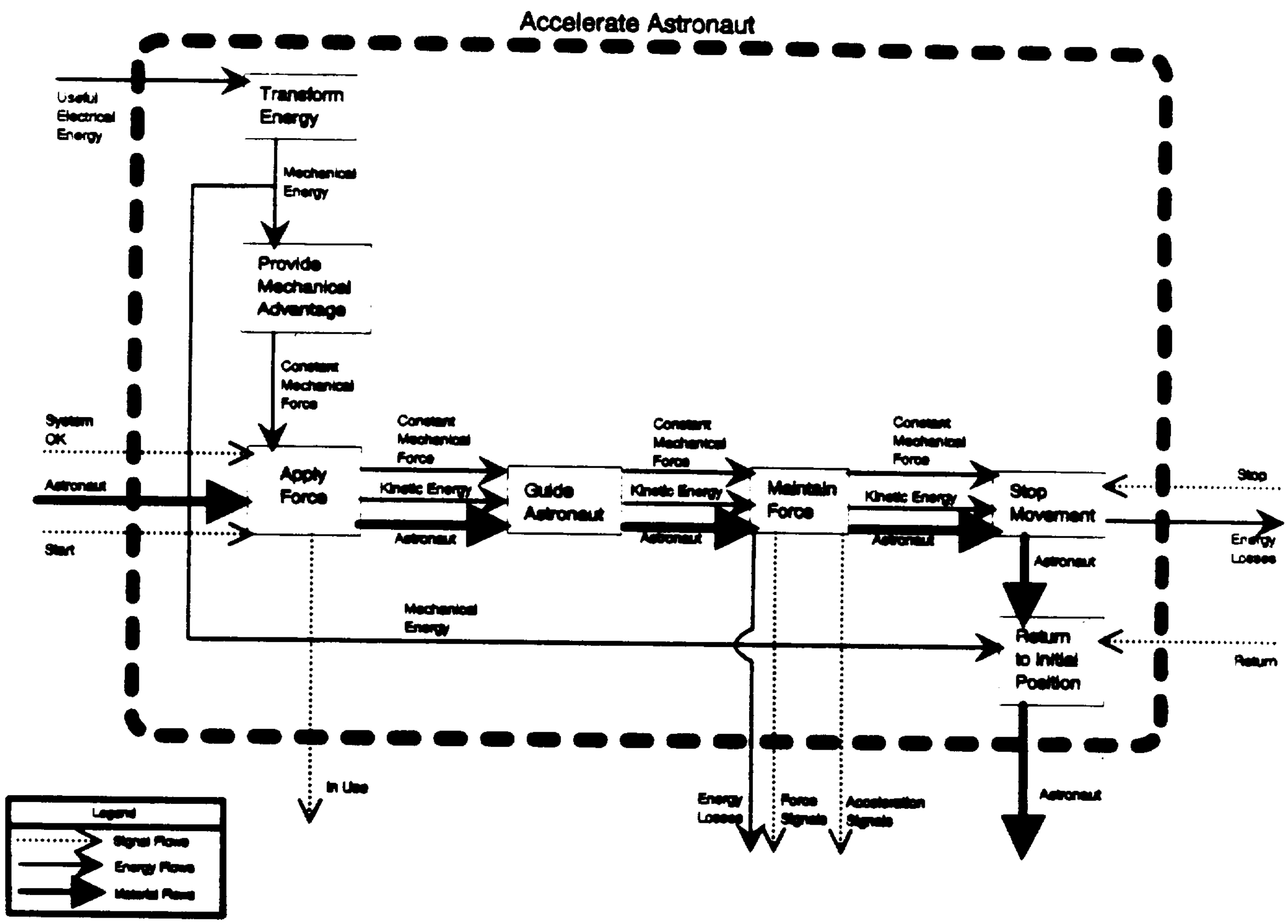


Figure 9: Accelerate Astronaut Function Structure

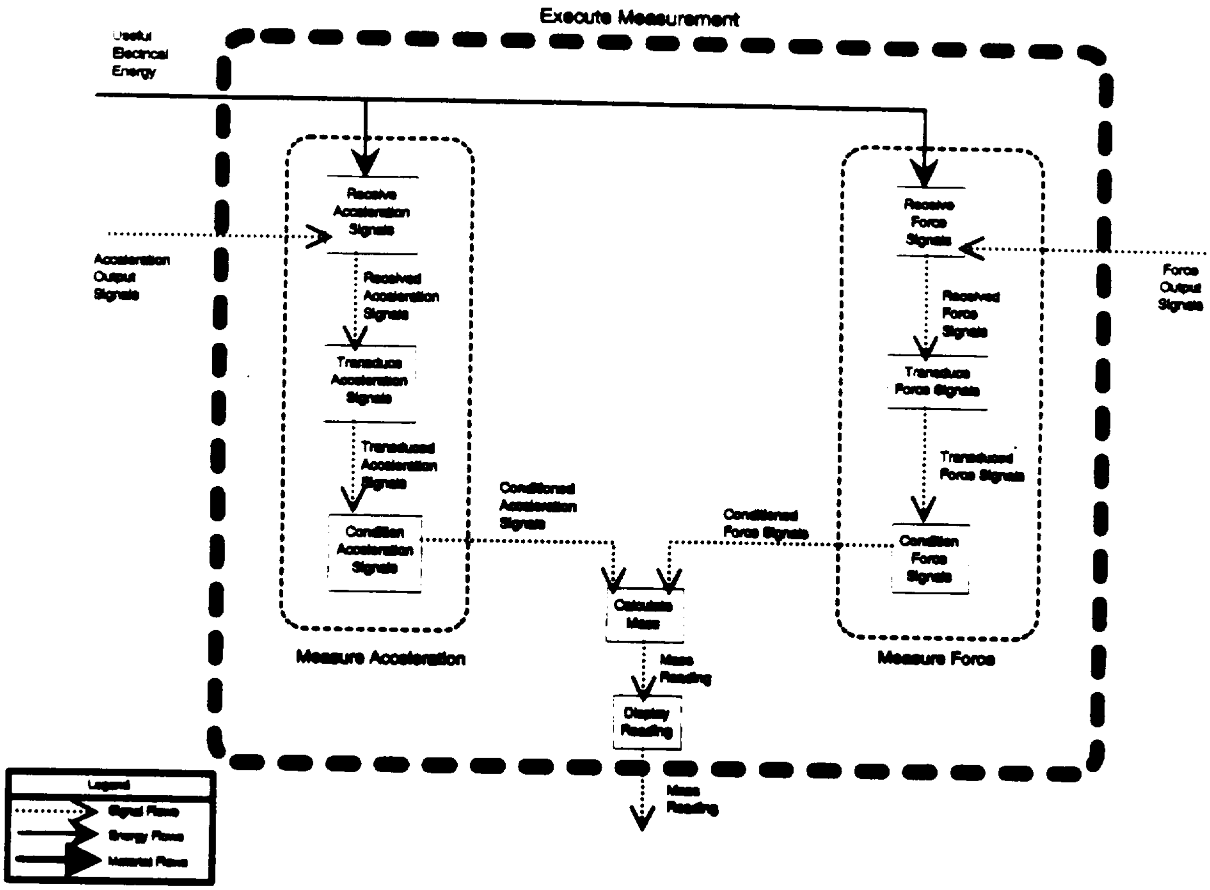


Figure 10: Execute Measurement Function Structure

Condition Acceleration Signals. The transduced acceleration signals might need to be conditioned into another form (e.g., amplification).

Conditioned Force Signals. The transduced force signals might need to be conditioned into another form (e.g., amplified).

Calculate Mass. Each set of acceleration and force signals is used to calculate the astronaut's mass, using the equation $F = ma$. 'F' is the measured force in Newtons, 'a' is the measured acceleration in meters per second squared, and 'm' is the mass in kilograms.

Display Reading. Once the final mass calculation has been determined, the mass is displayed so that the astronaut can see it.

Solution Principles

We have found various solution principles for the most important functions from our function structure. There are five main functions that are fundamental to the design of our mass measurement device. These various functions are presented in Figure 11 by a solution principle morphological matrix.

The first function is 'transform energy.' This is a process where the useful electrical energy from our power source is converted into mechanical energy that can be used to linearly accelerate the astronaut. 'Secure astronaut' describes the process of attaching the astronaut to the device that will be accelerated. This function is very important to the comfort and stability of the astronaut. The astronaut's body must be tightly secured to the seat or cart that is accelerated to eliminate any external body oscillations. If the external body oscillations can be eliminated, then the body, excluding internal fluids, can be considered part of the cart. This assumption will help simplify the mass calculation. The next function, 'accelerate astronaut,' is broken down into four categories. The acceleration category is probably the most critical function of the entire system. The accuracy, power required, comfort of the astronaut, and the magnitude of the ullage effect all depend on how we accelerate the astronaut. The 'apply/maintain force' category is a function that initially applies and then maintains the force needed to accelerate the astronaut. The direction of movement describes the direction that the astronaut will be accelerated. The body position category describes how the astronaut will be positioned during the measurement process. This will have a great impact on how comfortable the astronaut will be during the process. The last category, 'guide astronaut,' describes what structures will be used to keep the astronaut guided linearly throughout the entire acceleration and measurement process. How well the astronaut is guided will influence the linearity of the acceleration and any complications of frictional losses.

The 'stop astronaut' function involves decelerating the astronaut and bringing him to a complete stop. This function could play an important role in the safety and comfort of the astronaut and the accuracy of our measurements. The astronaut should be stopped without a sudden jar or jerk that would cause discomfort or possible injury. At the same time, it is also important to stop the astronaut in the shortest distance possible. Since the design is limited to 0.9144 meters for astronaut movement, the distance used to stop the astronaut is precious. Every inch used for deceleration could be used for more force and acceleration samples that would result in more accurate mass measurements. The mass measurement function is broken down into two categories: acceleration measurement and force measurement. The quality and accuracy of both of these measurements will determine the overall resolution and accuracy of our mass measurement device.

Solution Principles / Subfunctions	Categories	1	2	3	4	5
Transform Energy		Magnetic	Motor	Hydraulic	Pneumatic	Solenoid
Secure Astronaut		Buckles	Straps	Clamps	Human Force	Velcro
Accelerate Astronaut	Apply/Maintain Force	Rail Gun	Pulley / Winch	Gas Piston	Solenoid	
	Direction of Movement	Oscilating	X	Y	Z	

Figure 11: Solution Principles Morphological Matrix

	Body Position	Sitting	Standing	Prone	Fetal	Crouched
	Guide Astronaut	Magnetic Track	Mechanical Tracks	Bearings	Air Table	Pulleys
Stop Movement	Stop Movement	Rubber Bumper	Friction Brake	Magnetic Brake	Pneumatic Brake	Damper
Execute Measurement	Measure Acceleration	Accelerometer	Velocity / Time $a = \frac{Dv}{Dt}$			
	Measure Force	Magnetic Output $F \propto i$	Motor Output $T\omega = Fv$	Piston Output $F = \frac{P}{A}$	Solenoid Output $F \propto i$	

Figure 11: Solution Principles Morphological Matrix

Concept Variants

Table 5: Concept variants

Function	Variant # 1 (Motor)	Variant #2 (Rail gun)	Variant #3 (Piston)	Variant #4 (Solenoid)
Transform Energy	Motor	Magnetic	Pneumatic	Solenoid
Secure Astronaut	Straps	Velcro	Straps	Straps
Apply/Maintain Force	Winch	Rail gun	Air piston	
Direction of Movement	x-direction	x-direction	x-direction	x-direction
Body Position	Sitting	Sitting	Crouched	Sitting
Guide Astronaut	Magnetic track	Magnetic track	Air Table	Bearings
Stop Movement	Magnetic brakes	Magnetic brakes	Pneumatic brakes	Bumper
Measure Acceleration	Speedometer Chronometer	Accelerometer	Accelerometer	Accelerometer
Measure Force	Motor output	Magnetic output	Piston output	Solenoid output

All four concept variants have the astronaut in a sitting or crouched position. We eliminated the other positions because they would either let the astronaut wobble and disturb the measurement, or they would be too uncomfortable for the astronaut. We chose straps or Velcro™ to secure the astronaut because they would allow the quickest removal from the strongest hold.

In concept variant one (Figure 12), a motor is used to transform electrical energy into kinetic energy by causing a shaft to rotate at constant angular velocity. As the shaft turns, it winds a cable about itself, pulling the astronaut attached to the cable. This winch solution principle could use the motor's mechanical energy output to apply a mechanical force to the astronaut so we put these solution principles together. The astronaut is in a sitting position strapped to some kind of support. A magnetic track guides the movement. We thought this solution principle was one of the best to guide the astronaut because there would be no friction. Because magnetic tracks are used, we chose magnetic brakes to stop the movement. An accelerometer takes the acceleration measurement and the motor output gives the force.

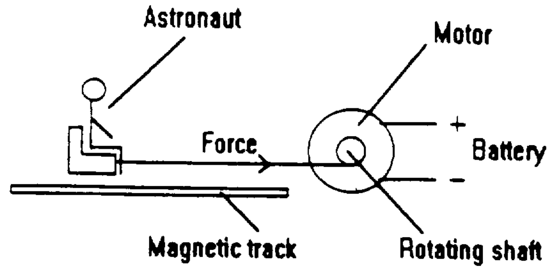


Figure 12: Concept variant one uses a motor-winch combination to apply force to the astronaut

In concept variant two, electrical energy is transformed to magnetic energy. The rail gun solution principle is best matched with this transformation principle because it uses a magnetic field to provide the force on the astronaut. Figure 13 shows how the rail gun would work. A current runs through two wires or rails that pass through a magnetic field. This creates a force on two bars placed on the rails. The astronaut is seated and strapped to a support on top of the bars. Because a magnetic track guides movement, we picked magnetic brakes to stop movement. An accelerometer measures the acceleration and the magnetic output gives the force.

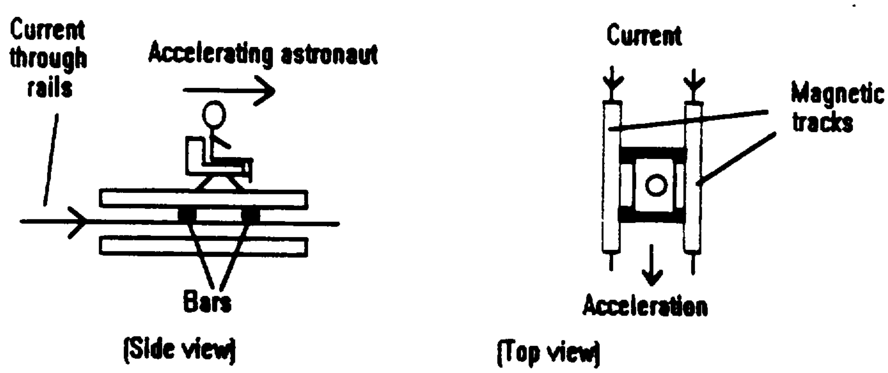


Figure 13: Concept variant two has a current running though a magnetic field to supply acceleration force

In concept variant three, electrical energy is transformed to pneumatic energy. An air piston best utilizes this form of energy to supply a pushing force on the astronaut (Figure 14). The astronaut is in a crouched position and attached to a support with Velcro™. An air table guides the astronaut's movement and pneumatic brakes stop the movement. We thought these solution principles were best for this variant because the energy is pneumatic. The air table would also eliminate friction. An accelerometer measures the acceleration and the force can be found from the piston output.

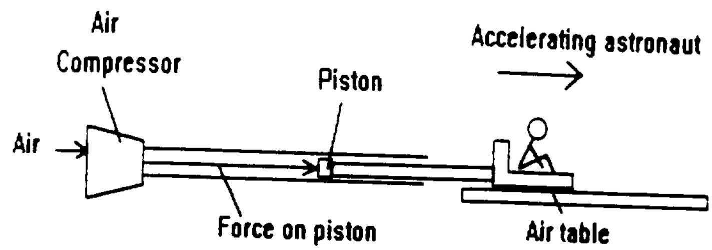


Figure 14: Air compressor provides a force on a piston to move astronaut (not to scale)

In concept variant four (Figure 15), electrical energy is again transformed to magnetic energy. A solenoid can also use this kind of energy. In this case the solenoid causes the magnetic field created by a current running though a coil to put a force on the astronaut's support. The astronaut is in a sitting position and strapped to the support. Bearings guide the astronaut's movement and a bumper stops the movement. Like the air table, bearings also keep friction from disturbing the path of motion. An accelerometer gives the acceleration and the force can be calculated from the solenoid output.

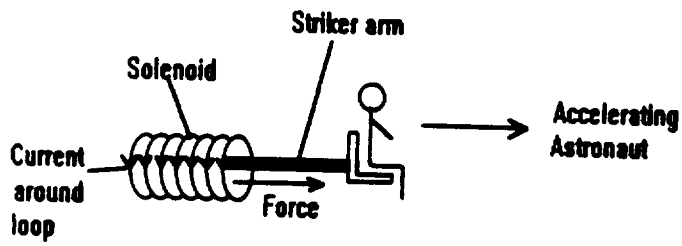


Figure 15: Current in solenoid creates magnetic field which puts a force on the astronaut.

Concept Variant Discussion

Rail Gun. Acceleration induced by a magnetic field seemed like a good idea until some basic equations were applied. For a rail gun type configuration, which has a magnetic field crossing fixed rails that have a moveable cart attached, applying a current creates a force described by:

$$F = iBl$$

where l = cart width across the track
i = current
B = magnetic flux density
F = force

We assumed a force of 10 N to be reasonable and estimated cart width at 0.5m, as well as a current of 10 amps. We first checked the equilibrium speed to see if the system would move at a high enough velocity. The equilibrium speed is described by

$$u = \frac{V}{lB}$$

where V = voltage
l = cart width,
B = magnetic field density

Since a B field induced by permanent magnets would be too large and require heavy magnets, we assumed that the B field would be induced by current traveling through a long wire. Then we calculated how far from a long thin wire we could experience the desired B field. This is described by

$$B = \mu_o H = \mu_o \frac{i}{2\pi r}$$

where r = the distance from the wire where the desired magnitude of the B field will be located
μ_0 = 4π*10E-7 Henrys/meters
i = current in the wire

Solving for r , we get

$$r = \mu_o \frac{i}{2\pi B}$$

For a force of 10 Newtons and an estimated cart width of 0.5 meters, if i = 10 amps, then B = 2 Tesla. The astronaut cannot safely be exposed to magnetic fields of this intensity. The equilibrium speed is 2.5 meters/second. This is enough to get the acceleration that we ~~need; however~~, the system would have to be 0.000001 meters away from the wire inducing the 2 Tesla field. This is an unreasonable distance. Solving these equations for different currents and magnetic field densities did not yield any reasonable results, so this concept variant is not feasible because either the B field or the current is too great [Cogdell, 1990].

Piston. An acceptable force needed to move the astronaut was calculated to be about 10N. This small force requires a low pressure. We looked at a catalog of various types of compressors and found they could produce a pressure range of 15-60 psi (101.3-414 kPa) [*McMaster*,]. We used the least possible pressure and calculated the necessary piston diameter:

$$A = \frac{F}{P} = \frac{10N}{101.325kPa} = 9.662 \times 10^{-7} m^2$$

where F = force
P = pressure
A = area

$$A = \frac{\pi d^2}{4}$$

where d = piston diameter

$$d = (4A/\pi)^{1/2} = (4(9.662 \times 10^{-7} m^2)/\pi)^{1/2} = 0.1mm.$$

This small diameter prevents using a compressor and piston to push the astronaut from being feasible.

The air piston could possible be used with a vacuum, pulling the astronaut by having a negative pressure differential ~~on the~~ sides of the piston rather than pushing the astronaut with a positive pressure difference. However, it would be hard to control the vacuum. For both the compressor and the vacuum, the volumetric capacity must be changed during the measurement to accelerate the piston. Varying the capacity requires varying the drive motor's rpm. Most electric motors run at constant or nearly constant speeds.

Solenoid. The next concept variant involved a solenoid to transform the electric energy from the power source into mechanical energy that can be used to linearly accelerate the astronaut. One of the advantages of using a solenoid is that it produces a constant force every time it is activated by the appropriate current. Unfortunately the force is constant only at given strike distances. The solenoid could possibly apply a continually increasing force if the astronaut were accelerated through the entire distance of the strike. A disadvantage of this idea is that most solenoids have a maximum strike distance of about 1.25 cm [Electronic, 1991]. This is not a long enough distance for the ullage effect to dampen out completely or for a sufficient number of force and acceleration samples. A special solenoid could be designed with a 2 to 3 foot striking distance to overcome these problems. The overall length of a solenoid is approximately three times the length of its striking distance. Therefore a custom designed solenoid that could successfully accelerate the astronaut would be about 8 feet long. A solenoid of these dimensions is not feasible for our size and mass constraints.

Another disadvantage of this concept variant was that the astronaut is guided with bearings. Even though bearings give positive, physical guidance, the friction caused by the bearings complicates mass calculations and our computer model. The energy losses caused by friction will vary for each astronaut due to the different force needed to accelerate each individual astronaut.

Motor-winch system. After grading the concept variants in the decision matrix, the team found that the variant with the highest grade by quite a margin is the motor-winch variant. The system has many unique attributes which raise it above other choices. The most singular feature is the way in which the system applies a force. The use of a winch allows a constant force to be applied to a body that is accelerating at a constant rate. None of the other variants are able to do this quite as easily as a motor-winch apparatus. All of the components are simple and commonly found in industry. The variant is not like others that require a sophisticated type of technology that may not be as reliable and as proven as an electric motor and a winch. The design team also felt that either the shaft of the motor, the connection from the winch to the cart, or the current into the motor can provide an accurate measurement of the force applied.

The basic concept involves a winch pulling a cart with a constant force at a constant acceleration. An electric motor drives a winch which is attached to a flexible tension line. The line is connected at the other end to a sliding cart. The cart is guided by magnetic tracks with poles opposite to ones attached to the cart. The tension line wraps around itself on the winch causing the torque radius to continually change. The motor will exert an increasing torque throughout the measurement process, however, the cart will speed up as the radius of the winch changes. A simple analogy to make this clearer is to think of how a tape recorder operates. When a tape recorder is rewinding, the speed of the tape increases as the tape accumulates on the reel. A film projector is another example.

The motor can be DC or synchronous AC. AC induction motors are too sensitive to torque changes [Cogdell, 1990]. Induction motors change their speed when the torque they apply changes. AC synchronous motors maintain their speed regardless of torque. If AC synchronous motors are not available, shunt connected DC motors maintain their speed sufficiently for the torque changes experienced in this application. Series connected DC motors are also too sensitive and should be avoided [Cogdell, 1990].

The DC motors that are available in the power ranges needed operate at much higher rpm than needed (around 15,000 rpm). In addition, the torque output from these motors is only about 0.05 Nm. The maximum torque required is approximately 0.5 Nm. In order to solve these two problems a gear box will be needed to slow down the angular velocity and raise the torque supplied by the motor. Belts are a possibility but they may stretch and allow the speed to vary. In order to provide a constant force and speed, a gear box is required.

A winch is necessary to transform the rotational energy supplied by the motor to a usable translational energy. The winch is also used to accelerate the cart or seat that the astronaut sits upon. By using a single channel winch the tension line is continuously wrapped upon itself. Rotating the winch at a constant angular velocity will then deliver an increasing velocity to the tension line. The tension line needs to be of a large enough diameter that when it wraps upon itself it will sufficiently change the radius. The tension line must be made of a material that will wrap around a winch of initial diameter on the order of 25 mm. At the same time the tension line cannot be so flexible that it will stretch upon the application of tension.

The tension line is connected to a seat or cart where the astronaut is located. The seat only needs to be large enough so that the astronaut has a place to attach his torso and feet. A back or head support is a good idea to help reduce the effects of ullage. If there is not enough room for such support its absence is not critical. Ullage effects in our MATLAB models (see Appendix A) have not been a problem. The models indicate that minimum restriction will suffice for the 5 N force being applied.

Straps are suggested for restraining the astronaut. Straps are quick and simple to use. Justification for this can be found by thinking about how long it takes for a person to get out of a car's safety belt, or the time required to remove oneself from an amusement park ride. Straps can also be altered to fit the person using them. This attribute helps meet the constraint for use with 5th percentile woman to 95th percentile male.

The magnetic track is suggested to minimize the energy dissipated by friction in the system. If permanent magnets or electromagnets are used to locate and guide a seat along tracks, friction will be kept to a minimum by the repulsive forces of the like poles. Magnets work well in space because they do not have to support the weight of the astronaut and apparatus only guide the system. Mass constraints could prohibit the use of permanent magnets because of their iron content. The tracks could be transformed into brakes by reversing the poles of the magnets. The attractive magnetic forces would pull the astronaut to a stop.

To measure the mass from this system, velocity, time, and force need to be measured. The acceleration of the cart can be measured by measuring the velocity of the cart at regular time intervals. High sensitivity speedometers can measure speeds less than 0.3 m/s with an accuracy of ±0.0003 m/s [Davis, 1992]. The force applied to the cart can be measured somewhere in the tension line by using a force gauge. Force gauges with a range of 10 N can be accurate to within ±.01 N [McMaster, 1992]. Assuming that three seconds are available for acceleration measurement, the time will have an accuracy of ±0.0001 seconds. Using uncertainty analysis the total accuracy of mass measurement can be found from the following equation [Bergman, 1994]:

$$u_m = \pm((u_v \cdot dm/dv)^2 + (u_F \cdot dm/dF)^2 + (u_t \cdot dm/dt)^2)^{1/2}$$

where m = mass, v = velocity, t = time, and F = force. By plugging in obtained values on the right hand side, the accuracy of mass measurement is found to be ±0.1 kg.

Accuracy is a constraint that is not fully met by the motor-winch system. The system does do a good job of meeting all the other constraints in the specification sheet. The design consists of distinct separate modules (i.e., motor, winch, seat). These separate modules allow less than two hours for set-up. As mentioned before, straps to secure the astronaut allow the astronaut to get in and out of the system quickly. No tools are required for assembly. The modules can be designed so that they can connect without tools. If any fasteners are needed, wing nuts can be used. The only tools required for maintenance would probably be for the motor. At most a screwdriver and a pair of wire cutters will be needed for maintenance.

Specifications that deal with the astronaut's comfort are easily met by the motor-winch system. The seated position that the astronaut must maintain is less comfortable than a natural posture, but it is better than the tight fetal position that is currently required of astronauts. The position resembles the position of a person sitting on a snow sled or in a toy wagon. The measurement only takes 4 to 5 seconds so that the position does not have to be held for more than five minutes. The linear acceleration the astronaut experiences involves no oscillation or rotation, which additionally adds to comfort of the astronaut.

The system requires two people to be present. One astronaut is seated in the apparatus while another astronaut performs the measurement. The system fits into any standard connections. A DC or AC hook-up for the motor and a connection to secure the track are the only connections required. The magnetic tracks will minimize wear and further the life of the system. The modularity of the system also allows damaged parts to be repaired without replacing the whole system.

A power constraint for this project was never decided upon, but with the motor-winch system it is doubtful that power is a concern. At most, the power required will be between 5 and 10 Watts, an amount that is less than most household appliances. Another critical specification is the mass and volume of the system. The largest sections by volume are the seat and track. The seat is estimated to be 450 mm x 450 mm x 40 mm. The track is estimated to be 2 m x 75 mm x 75 mm. Using these dimensions with the other components estimated to be much smaller, and assuming the track and seat can be stored in sections, the motor-winch system should have no problem fitting into two 0.057 m^3 storage bins.

Because nothing in the system is structurally critical, many of the components can be made of lightweight materials. The heaviest components of the system will be the magnets on the tracks. Allowing 3.4 kg for magnets leaves 3.4 kg for the rest of the system. Using catalogs and common household devices, the other components can be estimated by mass as follows: seat-0.9 kg, track-0.9 kg, electronics-0.9 kg, tension line-0.45 kg, motor-0.2 kg.

The motor-winch system is not as flashy as the other concept variants, but it solidly performs the required functions. The electric motor is a reliable and proven device for transforming electric energy into mechanical energy. The system secures the astronaut without problems. Straps to be used to secure the astronaut protect humans in crashing cars, they should have no difficulty securing a person subjected to a 5 Newton force. As for applying and maintaining a constant force, the motor-winch system is the best idea the team has come across to this point. The changing radius of the winch insures that force and acceleration of the cart will be constant. Guiding and stopping the astronaut is done effectively with a magnetic system. The motor-winch system is simple but reliable and functional.

Design Decisions

The criteria with which we graded the concept variants were accuracy, ergonomics, size, and power requirements. Accuracy can be further refined to include instrumentation, accuracy, and the ullage effect on accuracy. Ergonomics breaks into comfort and assembly, and size can be broken into mass and volume.

The same technique used to find weights for the process decision matrix was used to find weights for these categories. Accuracy seems to be the major design issue, so it was given a 0.5 weight. Ergonomics was assigned a 0.3 weight since it is the second most important consideration. Size and power requirements are about of equal concern, so they were both assigned a 0.1 weight.

Instrumentation accuracy was very important, so it was assigned a weight of 0.4, and the ullage effect was then weighted at 0.1. Comfort was an important consideration due to problems with a previous NASA design, so it was given a 0.2 weight. Assembly was not as important so it only received a 0.1 weight. Mass and volume were of equal concern, so they were each assigned a 0.05 weight. These are shown in the weight tree of Figure 16.

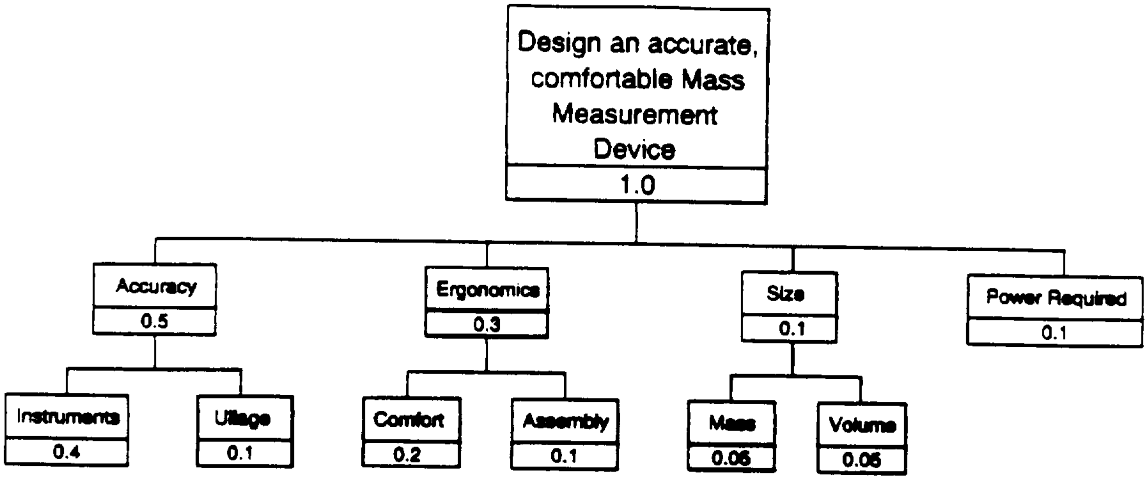


Figure 16: Concept variant weight tree.

Table 6: Linear acceleration concept variant decision matrix.

LINEAR ACCELERATION CONCEPT VARIANT DECISION MATRIX								
Spec	Instr'n	Ullage Effect	Comfort	Assembly	Mass	Volume	Power Req'd	Total
Concept Weight	0.4	0.1	0.2	0.1	0.05	0.05	0.1	1
1 Motor	95 38	95 9.5	90 18	80 8	95 4.75	90 4.5	75 7.5	90.25
2 Rail Gun	95 38	60 6	75 15	60 6	65 3.25	85 4.25	80 8	80.5
3 Piston	55 22	45 4.5	75 15	90 9	80 4	80 4	70 7	65.5
4 Solenoid	85 34	80 8	90 18	80 8	60 3	30 1.5	80 8	80.5

After construction of our decision matrix from the weight tree, we graded the various concept variants to determine the best design. Concept variant 1 (motor) received the highest score by approximately 10%. The resolution of the decision matrix is approximately 5%. Therefore, we believe that the first concept variant leads by a large enough margin to be considered the best design alternative. Grading our concept variants has forced us to consider the details of the various solution principles. We have determined some overall advantages and disadvantages of some of the solution principles. The solenoid offers a constant source of force but the size and mass needs to be reduced somehow. The motor offers a smooth, constant force on the astronaut and the force calculations are easily calculated from the motor torque and speed. The sitting position is more comfortable and natural than the crouched position. The magnetic and air tracks seem superior to the other guidance systems for the astronaut because of the frictionless cushion they provide for travel. We did not find an accelerometer capable of achieving the accuracies needed for our mass measurement, but a speedometer coupled with a chronometer could obtain the desired level of accuracy.

Conclusions

The design team applied the Pahl and Beitz methodology to generate a conceptual design for an space shuttle astronaut mass measurement device that will function in microgravity conditions. NASA will use the device to monitor the effects of microgravity upon the astronauts' bodies. It is not to be adversely affected by the ullage effect, or motion of bodily fluids. While many of the device constraints, including geometric, operational, and mass considerations, the team had to quantify 'comfort,' putting it in terms of body position, the time in that position, and the acceleration to which the astronaut is subjected.

We identified independence of the ullage phenomenon, accuracy, comfort and size as major design issues. We then generated a specification sheet to quantify the customer requests and design requirements and serve as a guide during the design process.

The team considered several general processes for mass measurement based on different quantities: bodily electrical properties, angular momentum, angular acceleration, linear momentum, linear acceleration, and average density. To facilitate further progress, we decided to pursue one general process rather than try to encompass all of them. We made our selection by initially eliminating those that were not feasible. These included the electrical properties and average density methods. We judged the remainder on the criteria of accuracy, independence of the ullage effect, and complexity and chose the linear acceleration process.

We refined the 'black box' global function structure into indivisible sub-functions and selected those that we deemed critical. For each of these we developed solution principles. Combining different solution principles, we generated four concept variants: motor-winch method, rail gun method, piston-driven method, and solenoid method. We judged these on seven criteria: instrumentation, ullage effect independence, comfort, assembly, mass, volume, and power required. The motor-winch system stood out over the other variants, the three of which were rated approximately equally.

Future Work

We generated several opportunities for future development and improvement during the design process. Primary among them is perfection of the motor-winch concept variant we finally selected. The tether used to connect the moveable platform and winch needs to be flexible in the transverse direction but not in the axial direction. That is, it must be bendable to facilitate winding around the winch, but should not stretch, as this could cause inaccuracy. Material selection will be important.

The use of a synchronous motor is an improvement that should be investigated. While it may be difficult to build a synchronous motor of such small size, such a motor would provide a constant speed, independent of torque applied. This way, the increasing radius would provide constantly increasing velocity, regardless of the mass of the astronaut.

The data sampling and acquisition feature of the system must be developed by electrical and computer engineering personnel. The device should be programmed to receive the information and perform the necessary calculations.

References

Barber, D. C., "Monitoring Body Fluid Distribution in Microgravity Using Impedance Imaging (APT)," Proceedings of the Annual International Conference IEEE Engineering in Medicine and Biology Society, vol. 13, (1991), pp. 1947-8.

Beitz, W., and Pahl, G., Engineering Design: a Systematic Approach (London: Biddles Ltd, Guildford and King's Lynn, 1992).

Bergman, T.L., Professor of Mechanical Engineering at the University of Texas at Austin (Austin: 2 February 1994), classroom lecture.

Cogdell, J. R., Foundations of Electrical Engineering (Englewood Cliffs, N. J.: Prentice-Hall, 1990).

Cogdell, John, Professor of Electrical Engineering at the University of Texas at Austin (Austin: 23 March 1994), personal interview..

Davis Instrumentation, catalog, vol. 58 (Blatimore: 1992).

Electronic Engineers Masters Catalog, 91-92, Vol. B (Stanford, CT: Omega Engineering, 1991).

Kistler Piezo Instrumentation, catalog (Amherst, NY.: Kistler Instrument Corporation, 1991).

McMaster Car Supply Company, catalog #98 (Chicago: 1992).

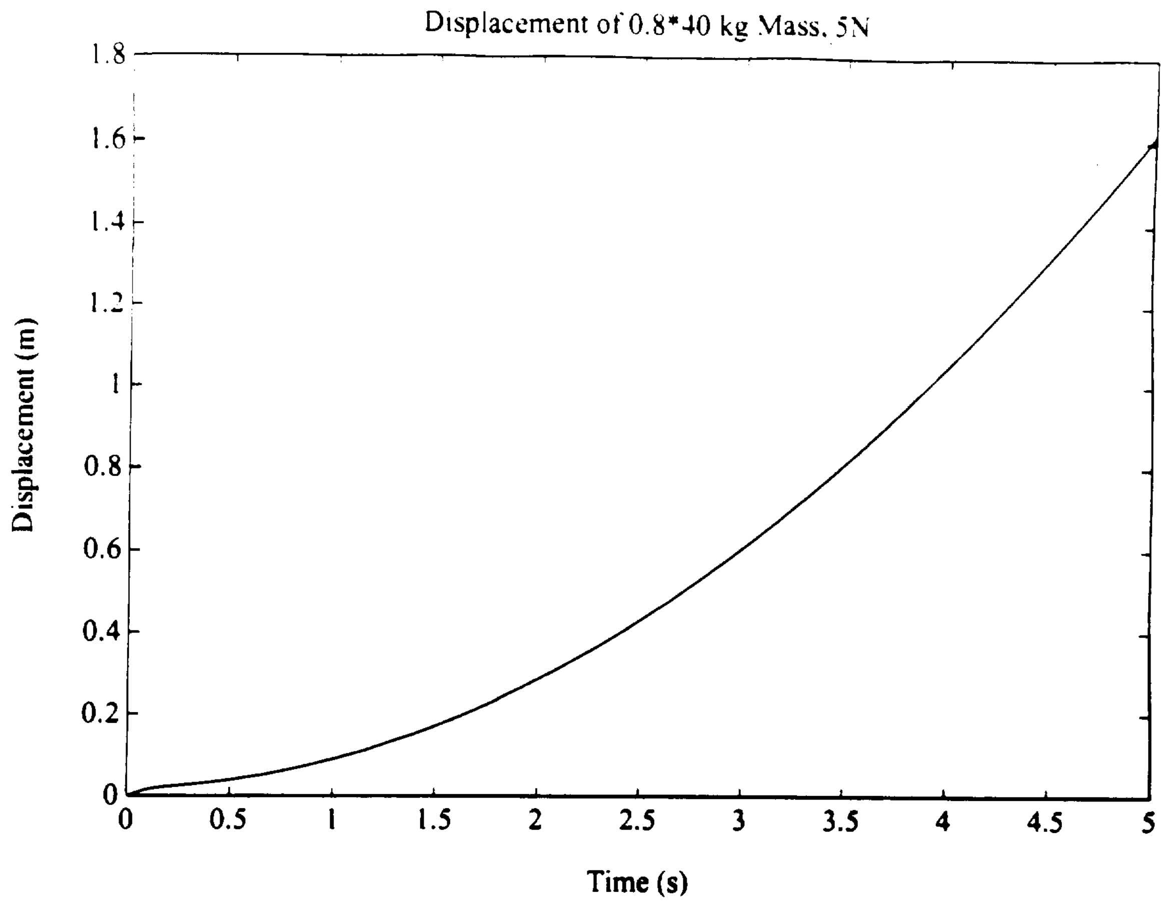
Meriam, J. L. and L. G. Kraige, Engineering Mechanics, Vol. 2, Dynamics, 2nd edition (New York: John Wiley and Sons, 1986).

NASA Standards 3000, vol.1, revision A (March 1988).

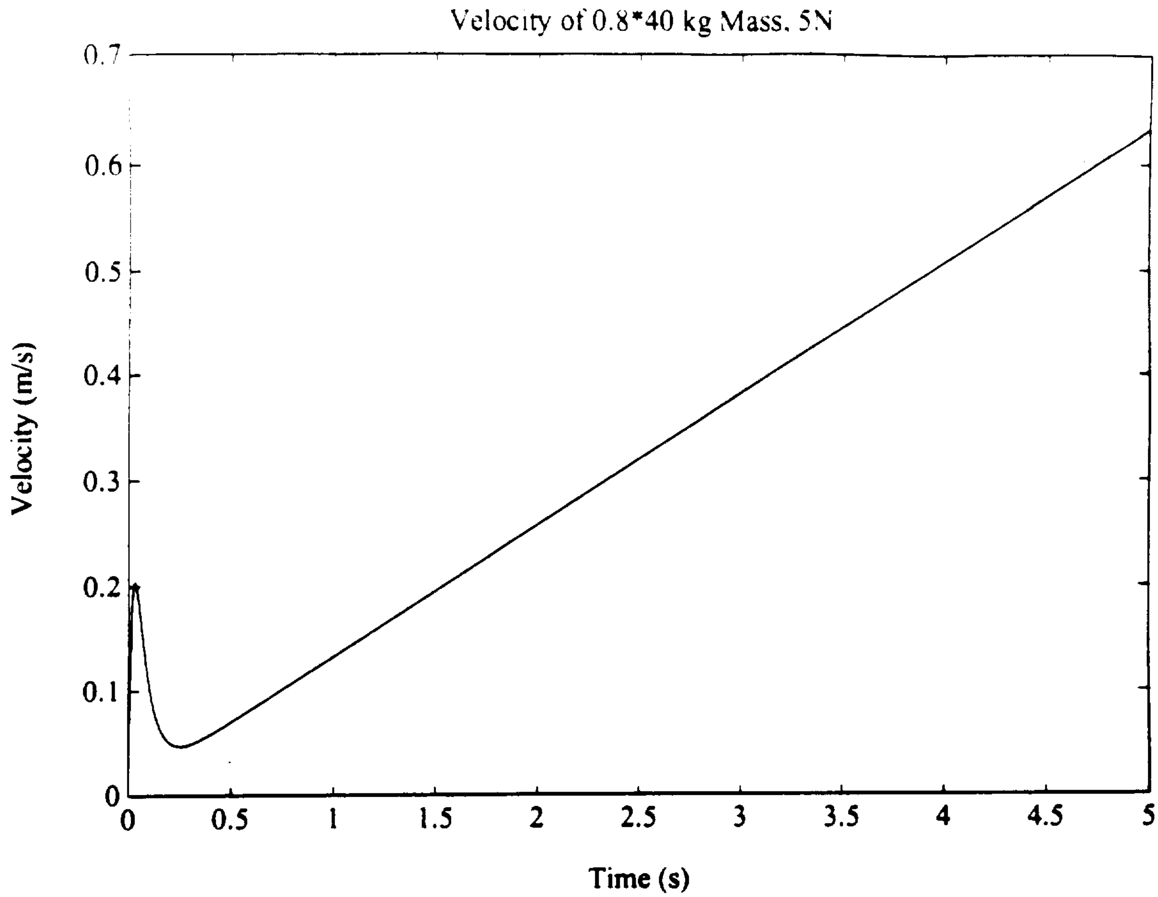
Norrell, Jeff, NASA liaison (Austin: 3 March 1994), personal interview.

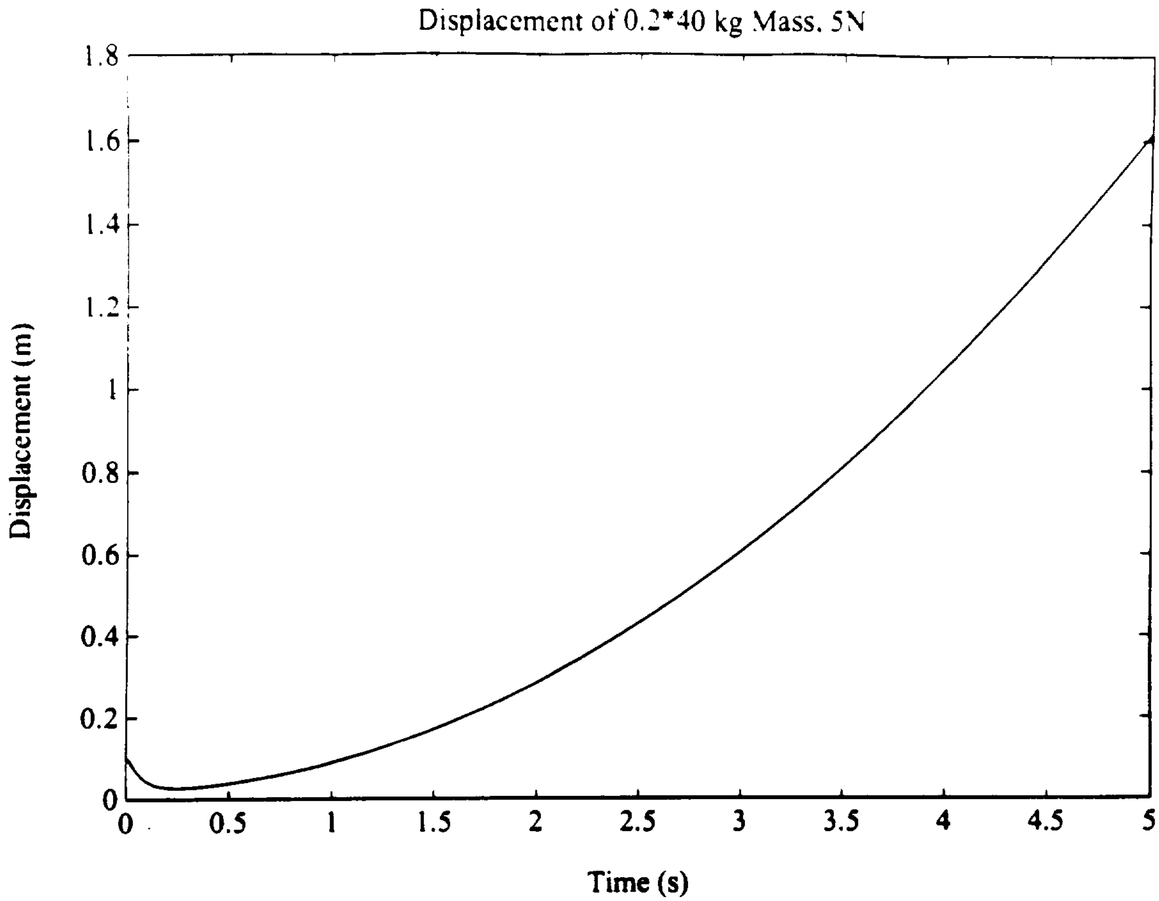
Pearce, J. A., Professor of Electrical Engineering at the University of Texas at Austin (Austin: 23 March 1994), personal interview.

Appendix A

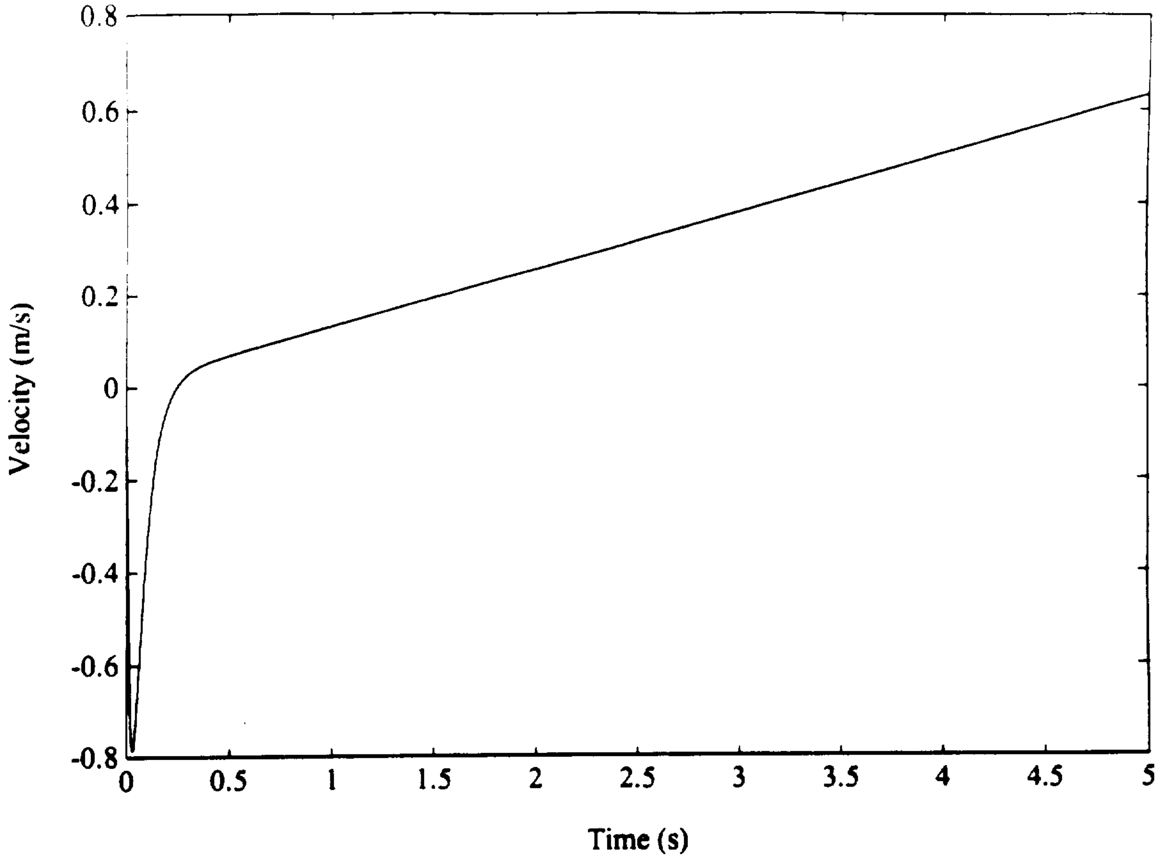


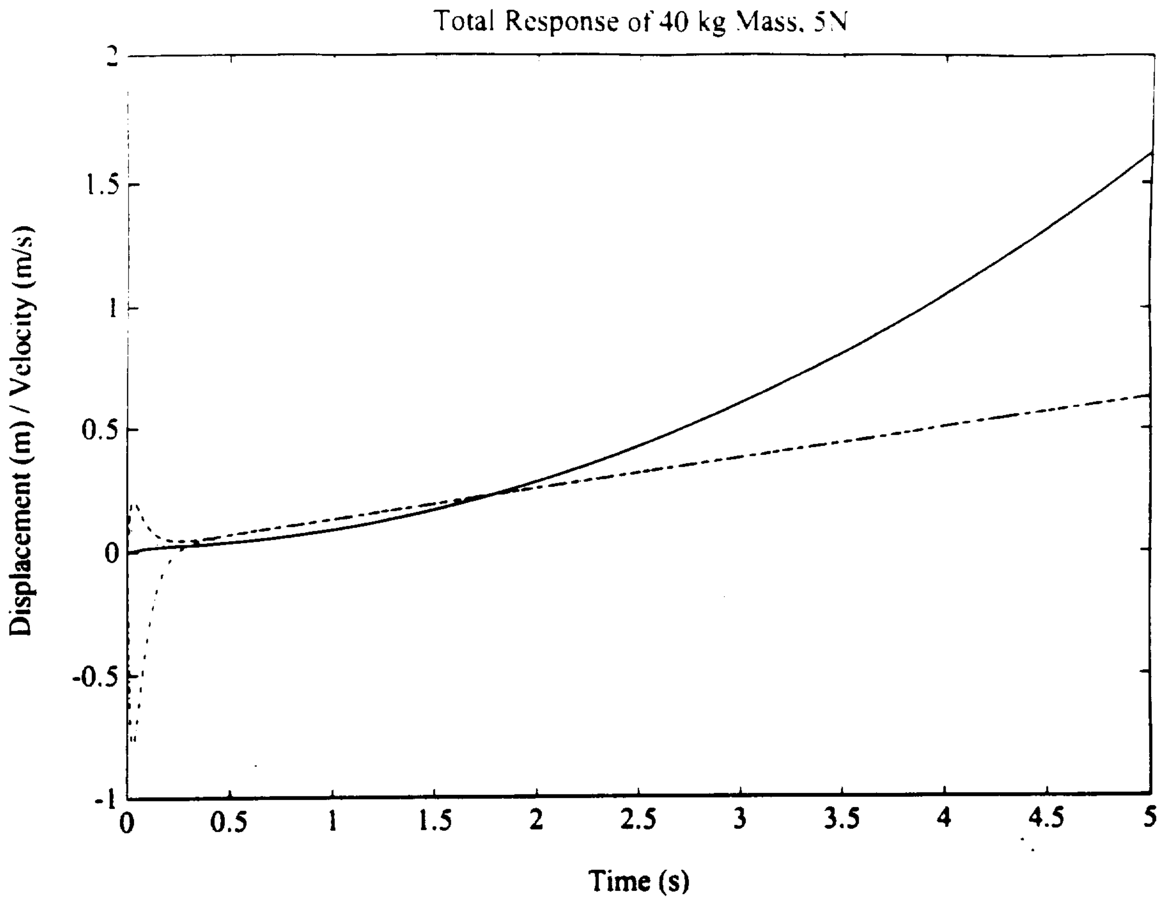
Displacement of 0.8*40 kg Mass, 5N
Displacement (m)
Time (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Velocity of 0.8*40 kg Mass, 5N
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

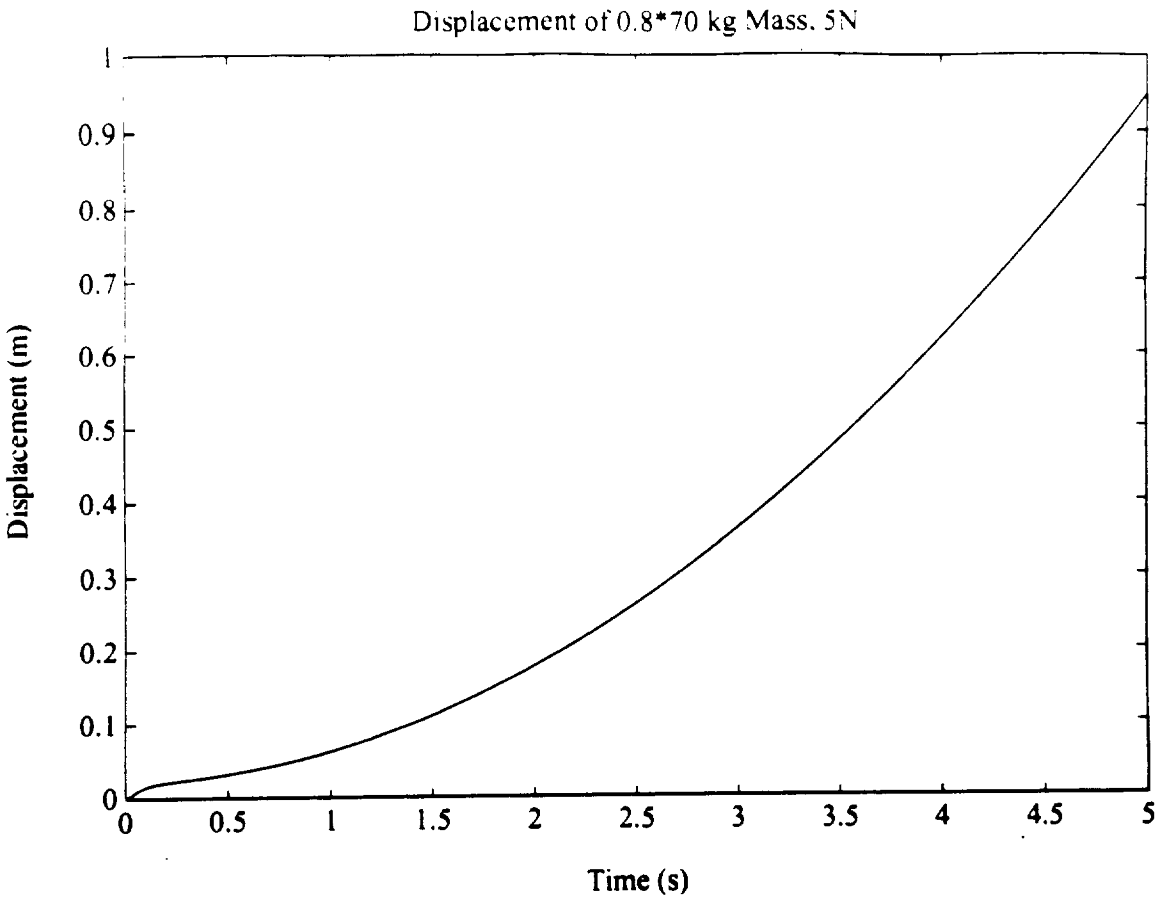

Displacement of 0.2*40 kg Mass, 5N
Displacement (m)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)

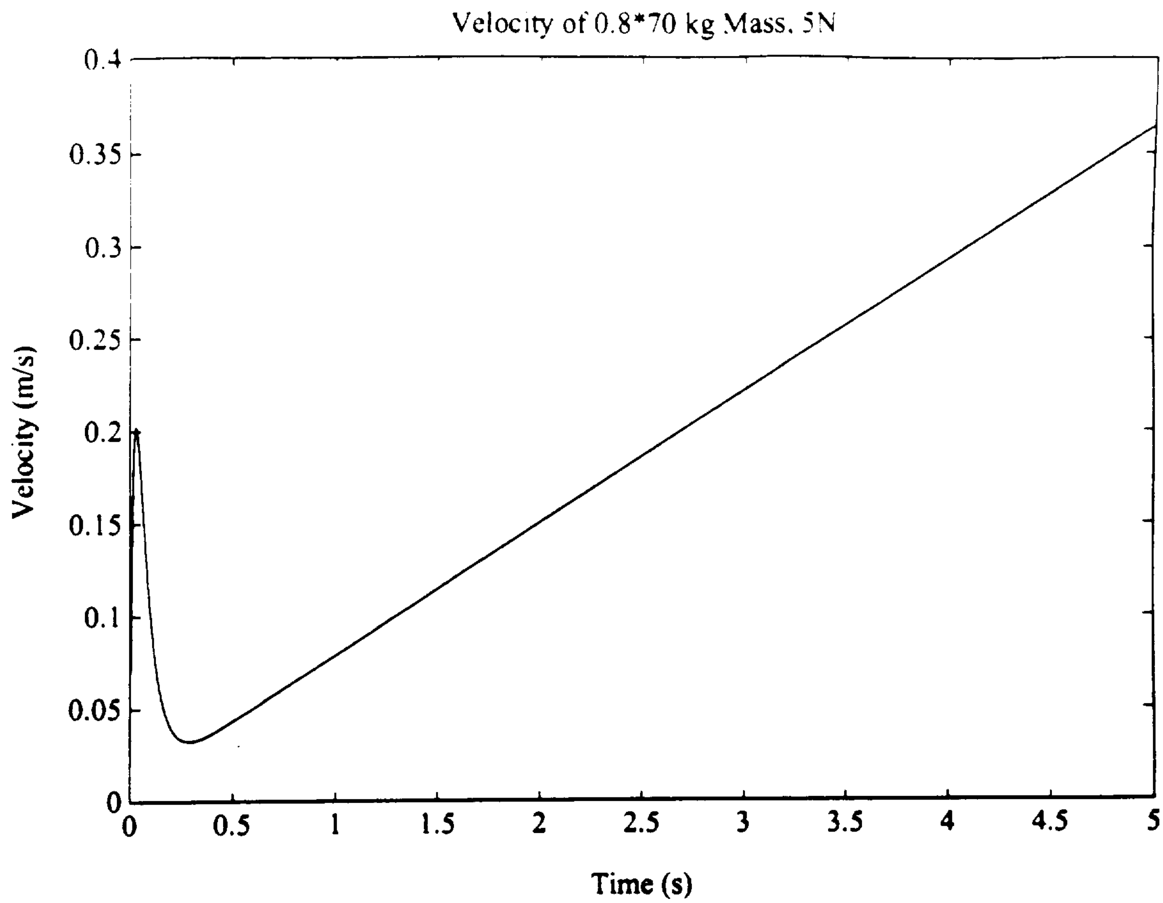
Velocity of 0.2*40 kg Mass. 5N

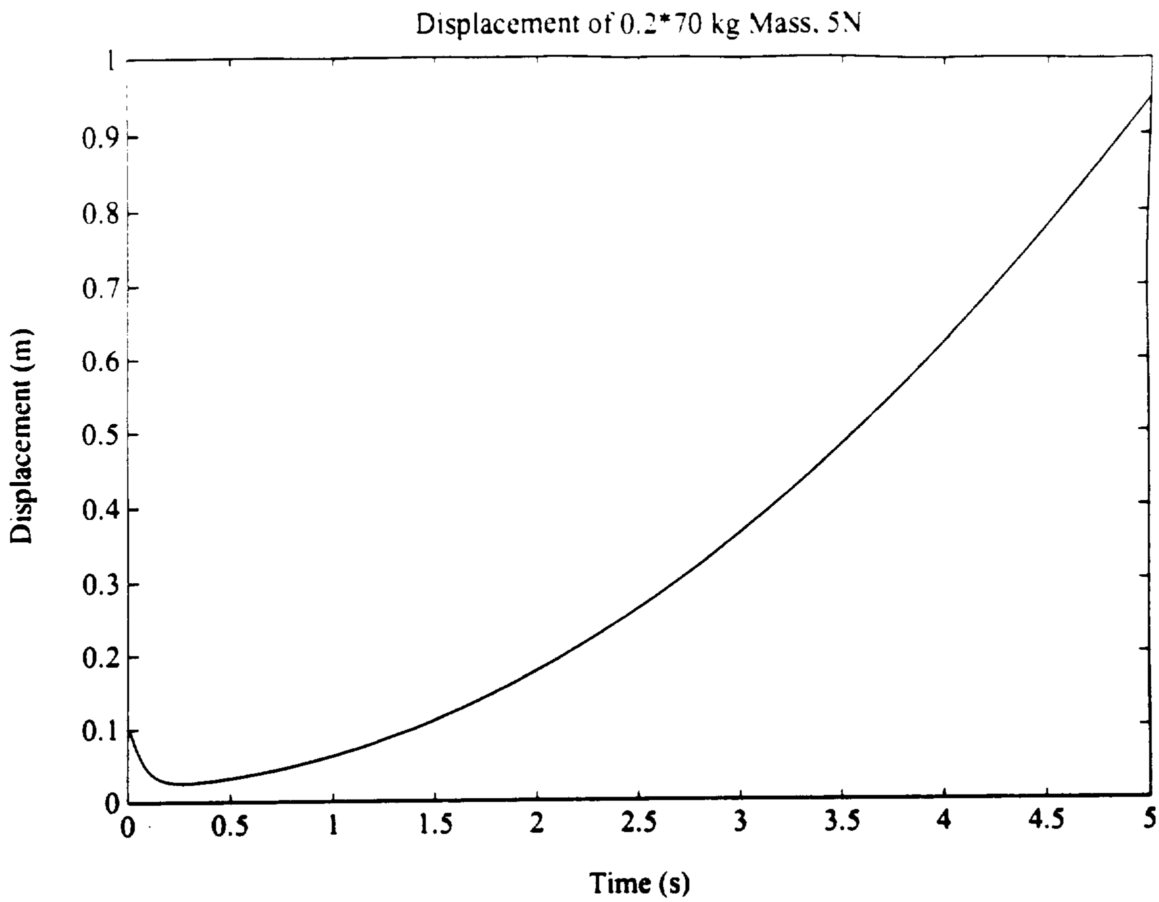


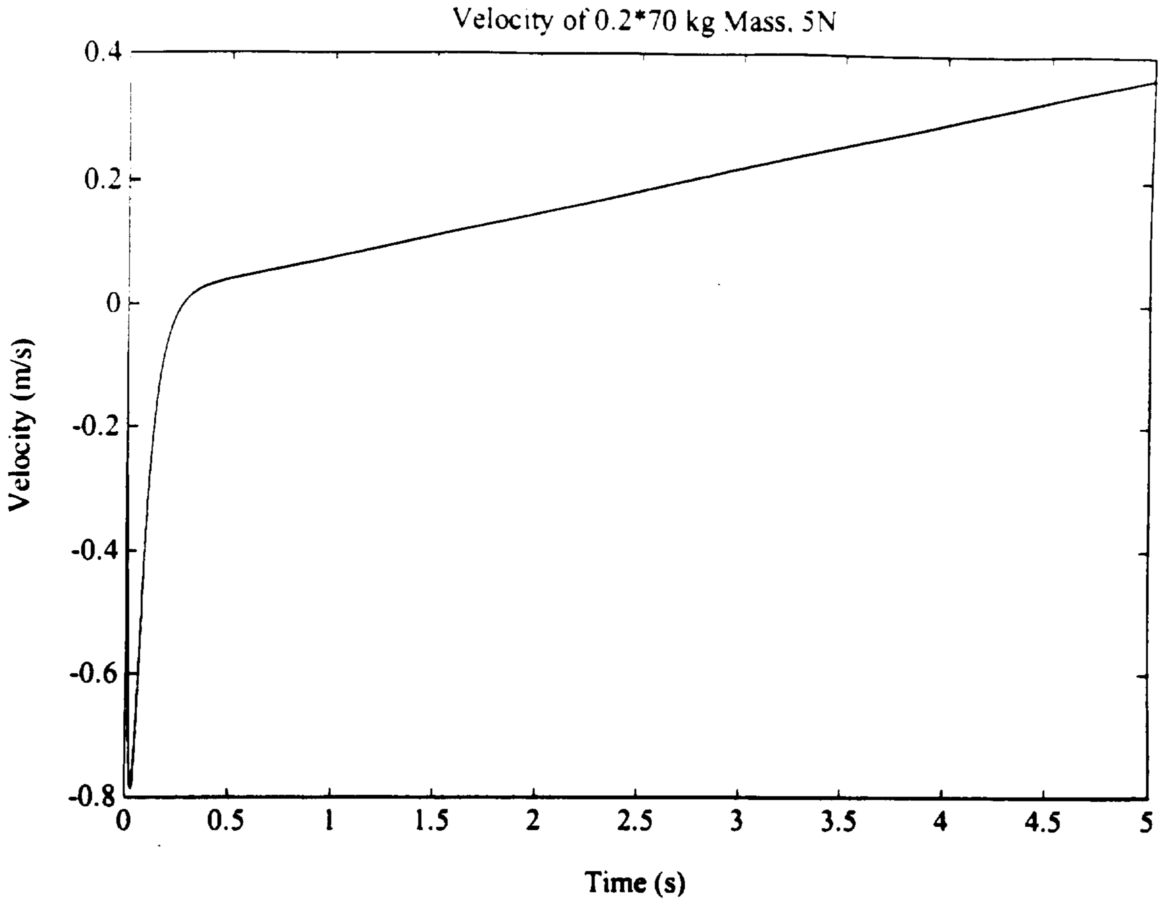


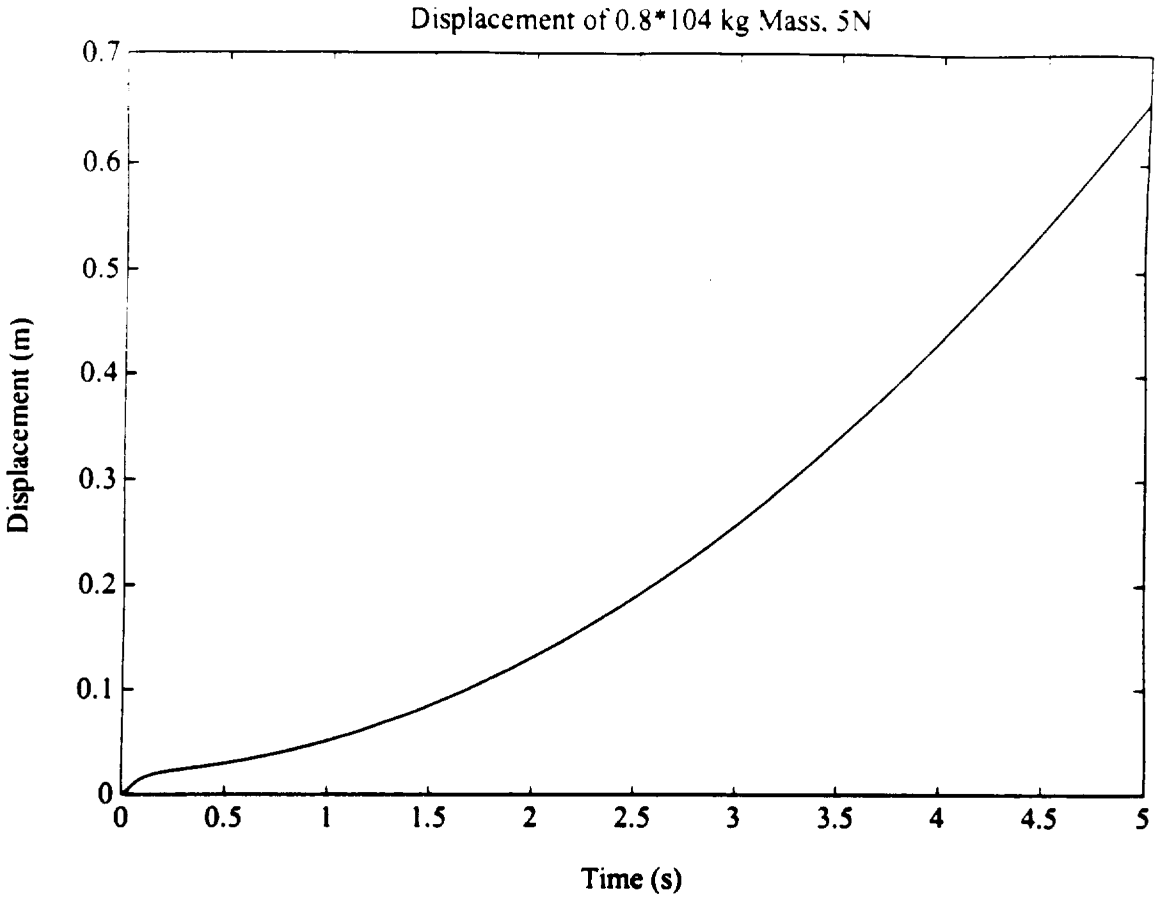
Total Response of 40 kg Mass, 5N
Displacement (m) / Velocity (m/s)
Time (s)
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

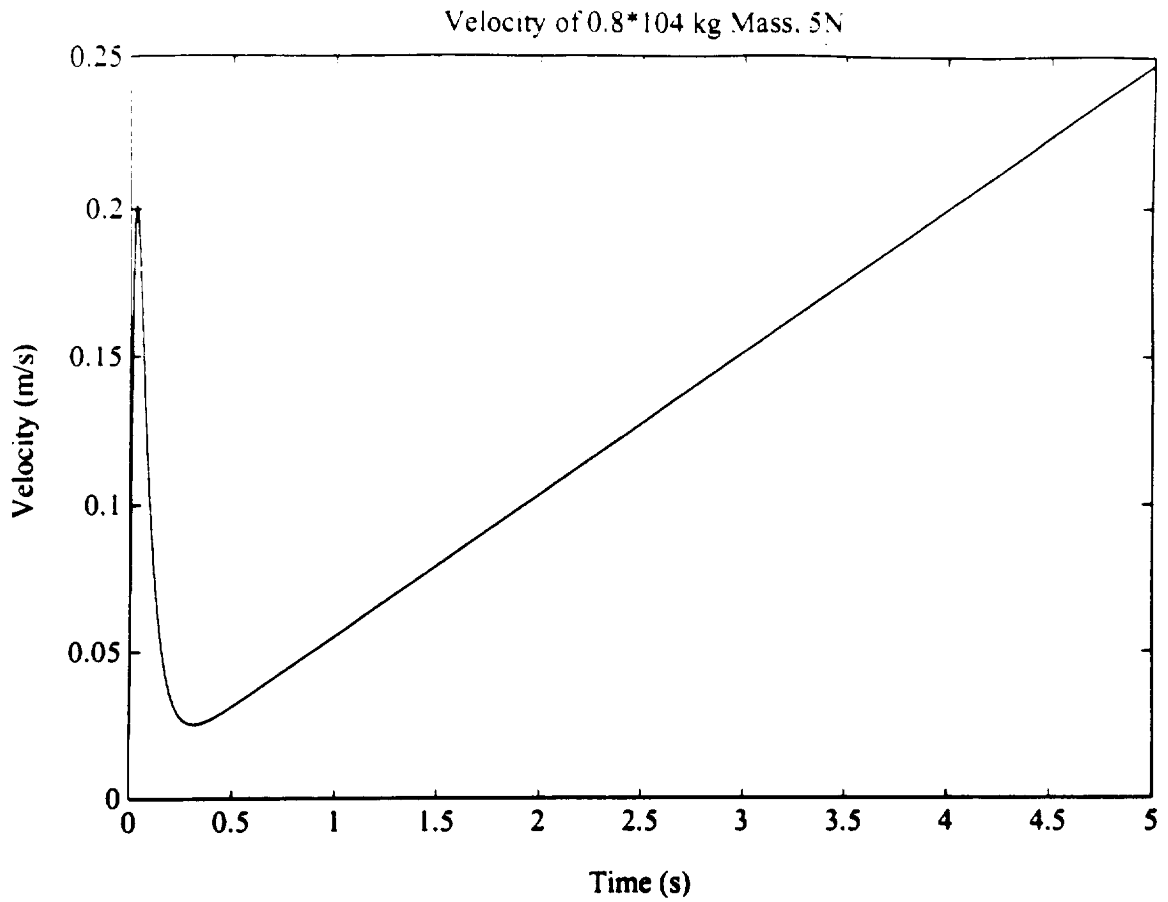

Displacement of 0.8*70 kg Mass, 5N
Displacement (m)
Time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

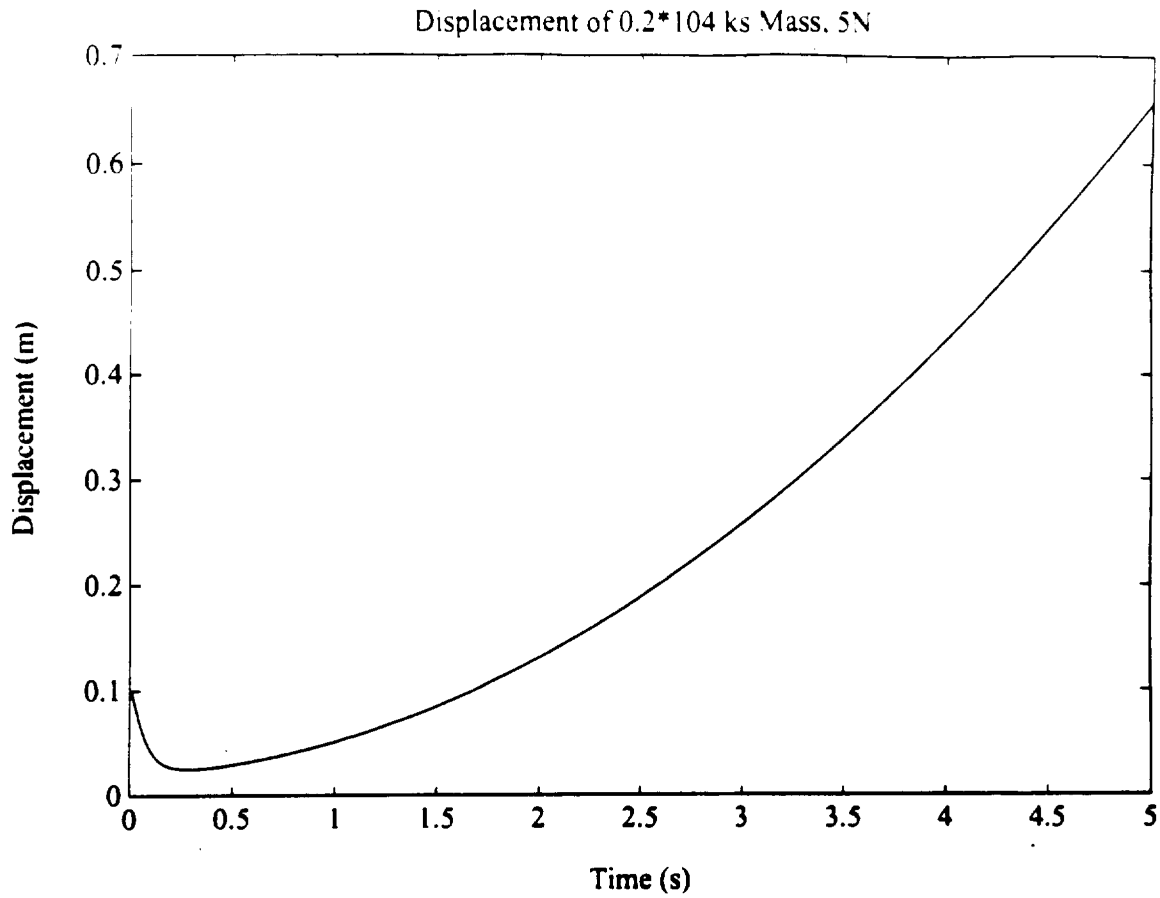

Velocity of 0.8*70 kg Mass, 5N
Velocity (m/s)
Time (s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Displacement of 0.2*70 kg Mass, 5N
Displacement (m)
Time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

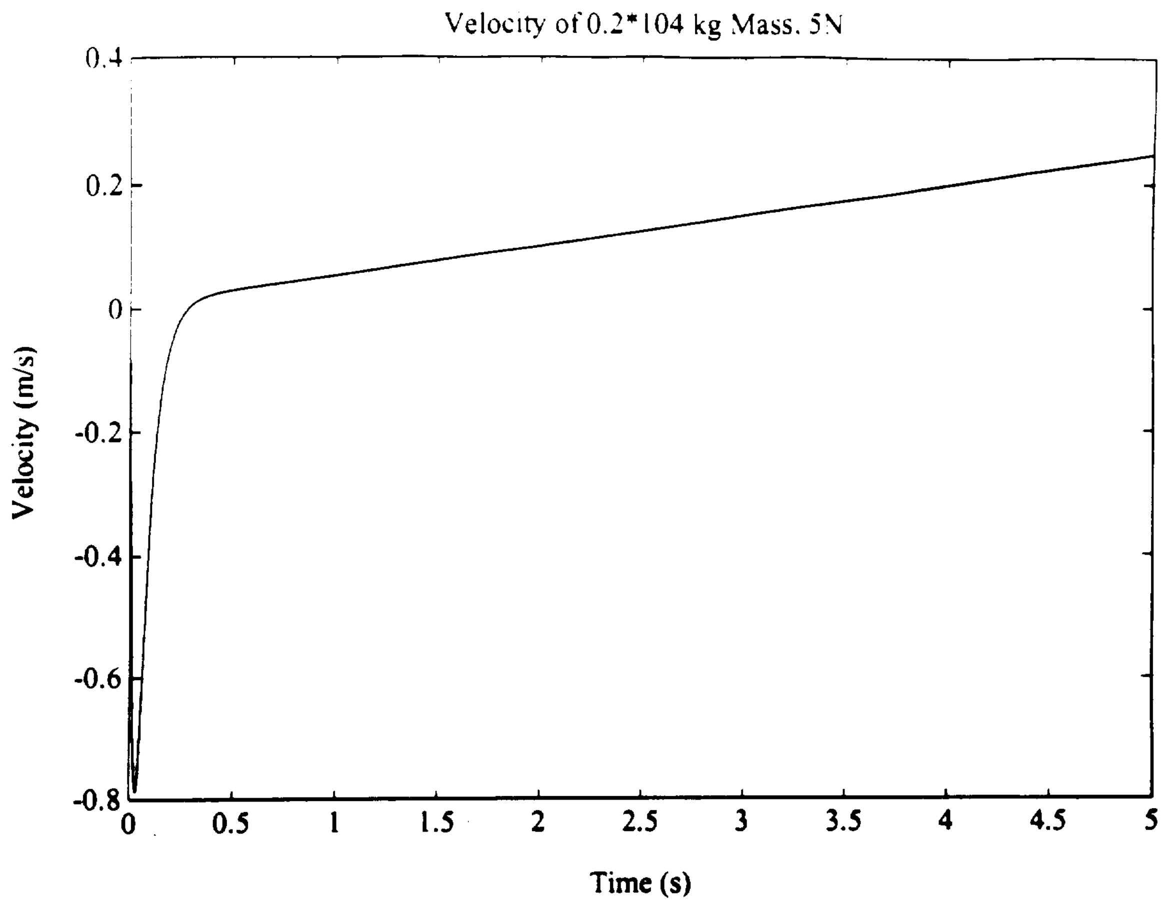

Velocity of 0.2*70 kg Mass, 5N
Velocity (m/s)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)

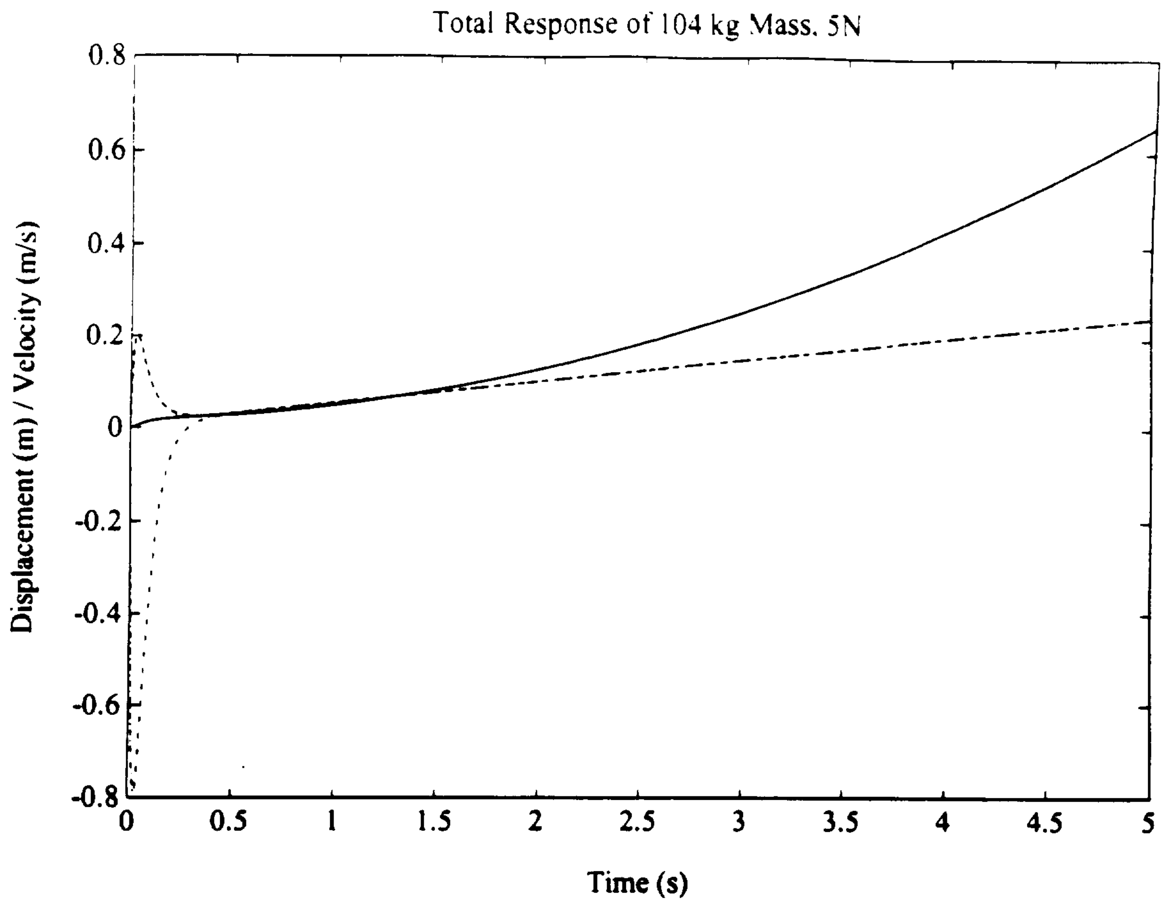

Displacement of 0.8*104 kg Mass. 5N
Displacement (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)


Velocity of 0.8*104 kg Mass, 5N
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Displacement of 0.2*104 ks Mass. 5N
Displacement (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)


Velocity of 0.2*104 kg Mass. 5N
Velocity (m/s)
Time (s)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Total Response of 104 kg Mass, 5N
Displacement (m) / Velocity (m/s)
Time (s)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Appendix B

Calculations: Derivation of Equations for MATLAB

Given: Idealized model shown, $f = 2\text{Hz}$, $\zeta = 0.5$, m = astronaut mass.
x_1 = displacement of 0.8m mass, x_2 = displacement of 0.2m mass.

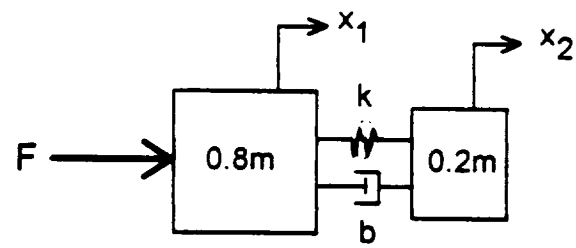


Figure 17: Free body diagram of accelerated astronaut.

Determination of spring stiffness 'k' and damping effect 'b:'

$$k = m\omega_n^2 = m(2\pi f)^2 = m(2(3.14)(2))^2 = m(12.57)^2 = 157.9\ m\ \ (N/m)$$

$$b = 2\zeta\omega_n m = 2\zeta(2\pi f)m$$

$$= 2(0.5)(\ 2(3.14)(2))m$$

$$= 12.57m\ (Ns/m).$$

Derivation of motion equations:

Applying a constant force 'F' to the 0.8m mass as shown:

$$\Sigma F_x = ma: \quad 0.8mx_1'' + bx_1' - bx_2' + kx_1 - kx_2 = F$$

$$0.2mx_2'' + bx_2' - bx_1' + kx_2 - kx_1 = 0.$$

Substituting for 'k' and 'b' and dividing through by 'm', we can then obtain a set of four first-order equations:

$$x_1' = x_2'$$

$$x_2' = 1.25(F(t)/m) - 15.7x_2 + 15.7x_3 - 198 + 19891$$

$$x_3' = x_4$$

$$x_4' = -63y_2 + 63x_2 - 790x_3 + 790x_1$$

where x_1 = displacement of 0.8m mass

x_2 = velocity of 0.8m mass

x_3 = displacement of 0.2m mass

x_4 = velocity of 0.2m mass