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ONE-DIMENSIONAL TESTBED FOR COULOMB CONTROLLED SPACECRAFT STUDIES

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ONE-DIMENSIONAL TESTBED FOR COULOMB CONTROLLED SPACECRAFT STUDIES

Carl R. Seubert* and Hanspeter Schaub†

This paper discusses the preliminary results of a novel testbed developed to examine relative motion of craft using electrostatic or Coulomb forces. The Coulomb Formation Flight (CFF) concept uses active charge emission to control the naturally occurring spacecraft potential in space to maintain desired separation. These forces are on the order of milli-Newtons and can strongly influence relative motion of geostationary satellites dozens of meters apart. Simulating such charged relative motion in a terrestrial environment is very challenging. The test bed consists of a non-conducting one-dimensional hover track which can levitate a charged craft. With a secondary charged object and the ability to change the potential it is possible to actuate the suspended craft and study the relative motion due to charge. The challenges of constructing this first generation electrostatic actuation testbed are outlined, including the mechanics of constructing the hover track, sensing the position of the cart, limiting the airflow supply as well as designing the cart which carries an electrostatic charge. Gravity disturbances are characterized and presented with test run data as well as preliminary results demonstrating that the Coulomb testbed successfully achieves electrostatic relative motion actuation.

INTRODUCTION

The research and development of distributed spacecraft systems continues to grow. The prospects of spacecraft flying in formation are exciting and propitious with a handful of missions in operation and numerous studies and applications in the planning phase.[1,2] Spacecraft formation flight architectures can be used to generate large sensor baselines for interferometry applications or scientific studies. It also aids the development of distributed network systems in space, cooperative control, and provides system redundancy. Of particular interest here is formation flight in the order of dozens of meters separation distances, including spacecraft flying in close proximity, deployment, rendezvous and docking, and tethered spacecraft systems. A challenge with these closely operated distributed spacecraft missions is the control mechanism required to perform and maintain the formation.

Detailed in this paper is a testbed designed to explore the electrostatic or Coulomb thrusting concept. Coulomb thrust is an actuation method to control the relative separation distance of spacecraft flying in close proximity (< 100 m). Through active charge emission of ions or electrons, the naturally occurring spacecraft electrostatic potential is controlled to desired values.[3,4] By controlling the polarity and charge level on each craft the relative forces can be manipulated to maneuver each craft within the formation. The major advantages of Coulomb relative thrusting are that it offers precise control with essentially no propellant (expels low mass ions or electrons) and has no plume impingement concerns while requiring only Watt levels of power.[4,5,6] Figure 1 illustrates a very simple two-craft Coulomb spacecraft formation example.

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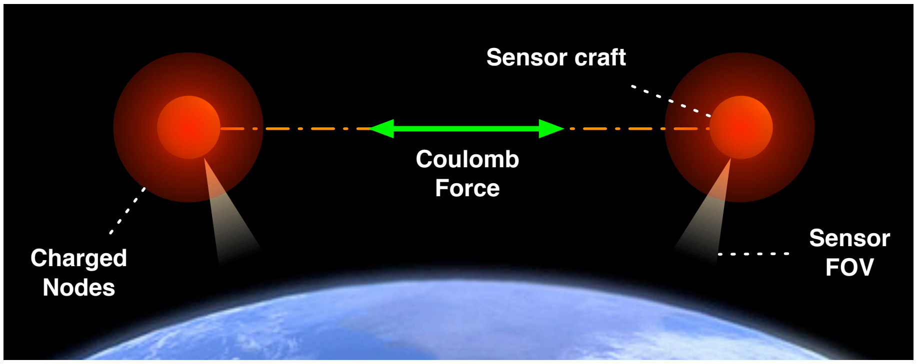

Figure 1 Two sensor nodes using Coulomb forces to provide the necessary formation separation distance.

A current formation flight missions is CLUSTER[7] which orbits four spacecraft with separations greater than 100 km. This mission involves scientific measurements of the local plasma environment. The spacecraft incorporate an ion emitter to precisely and actively control their potential, maintaining equal charge to their changing environment.[3] This charge control hardware is similar to what is envisioned for Coulomb controlled spacecraft. The charge level accuracy and adjustment speed of the CLUSTER spacecraft are much greater than what is needed for Coulomb controlled spacecraft. Other formation flight missions include GRACE which flies two spacecraft separated by approximately 220 km $\pm$50 km in an along track configuration.[8] The enhanced formation flying concept of EO-1 with Landsat-7[9, 10] were flown at a separation distance of 450 km. All these missions have used a conventional chemical propulsion system for attitude and/or orbit control.

A proposed mission is the NASA Goddard Stellar Imager, which is a constellation of up to 30 "mirror" spacecraft across a baseline of 500 m producing 0.1 milli-arcsec angular resolution.[11] Other potential missions include PRISMA which is intended as a technology demonstration of formation flight and in-orbit servicing[12] and the synthetic aperture radar mission of TerraSAR-X and TanDEM-X flying in configuration down to 200 m.[13] There is potential for these and other future formation flight missions to utilize the Coulomb thrust techniques that are being examined with this testbed research.

Coulomb control methods could also be applied to space-based deployment mechanisms and tethered systems, and ultimately investigated with this testbed. The current NASA JPL study leading to the proposed Terrestrial Planet Finder (TPF) could potentially use this technology. The telescopic array may utilize a single connected structure with node separations < 40 m or an array of spacecraft flying in formation with anticipated separations of a few hundred meters.[14]

There are numerous studies into the guidance, navigation and control of spacecraft flying in formation that fundamentally could benefit from Coulomb thrust applications and the findings of this hardware testbed. Reference 15 looks at relative motion techniques for spacecraft flying in formations with separations less than 1 km. There are also developments into autonomous control schemes for close proximity maneuvers such as those needed for operations involving the International Space Station (ISS).[16]

There are a number of testbeds that have been developed to simulate spacecraft in operation,

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with those highlighted here used specifically for formation flight studies. JPL's Formation Control Testbed (FCT) is a flat floor (7.3 m x 8.5 m) that enables robots with linear air-bearing pads to undergo near frictionless linear motion. The testbed does not simulate an environment of space but does incorporate ceiling mounted pseudo stars and allows for distributed system communication, sensing and control.[17] NASA Marshall space flight center also has a flat floor testbed that has been used to study formation flight scenarios such as the MIT SPHERES project.[18] The SPHERES spacecraft systems have demonstrated close proximity formation flight in terrestrial testbeds as well as within the confines of the ISS.[19] Stanford's Aerospace Robotics Laboratory also uses a granite table top (3.65 m x 2.74 m) that is used with air-bearing-based spacecraft for formation studies in a terrestrial environment.[20]

All these testbeds are intended to simulate a formation control strategy utilizing more traditional chemical propulsion methods to maintain geometry. Thruster use has the challenge of a finite propellant supply. Further, if the craft are operating in close proximity dozens of meters apart, there is also a potential for spacecraft and instrument contamination from thruster exhaust plumes. The electrostatic or Coulomb control concept is an alternate actuation method to the use of these thrusters as it uses negligible propellant, and has no concern for contamination of neighboring spacecraft.

Theoretical studies analyzing the prospects and performance of the Coulomb controlled spacecraft formation remain an ongoing area of research.[4,21,22] Numerical simulations indicate that Coulomb forces can be successfully used to maintain free-flying formations as well as alternate applications such as collision avoidance[23] and for tethered Coulomb structures.[24] A key step in developing the concept of Coulomb controlled spacecraft formations is to develop a testbed to perform Coulomb thrust experiments in a terrestrial environment.

This paper presents the developments of the hardware testbed designed specifically to demonstrate this actuation of a vehicle under Coulomb forces. This is a challenging step in the advancement of Coulomb thrusting for a number of reasons. Primarily, a terrestrial environment inherently incorporates friction and other disturbance forces which can be of same or higher magnitude as the Coulomb forces produced. There are also the challenges of safely generating and operating charged controlled vehicles with charge densities to allow sufficient Coulomb force for motion.

In particular, the testbed consists of a one-dimensional non-conducting hover track which levitates a charged vehicle with minimal friction. A second, stationary charged sphere is placed adjacent to the track, and provides a means to generate Coulomb forces onto the hovering vehicle and control its motion. The challenges involved with this testbed include constructing the track out of suitable non-conducing material, levitating the charged craft using a minimal amount of air, controlling the spacecraft charge without having access to space-based charging techniques, as well as constructing the charge test vehicle.

Such a testbed allows for cost-effective charged relative motion experiments to be performed using simple charge feedback control laws. It allows the study of electrostatic effects and the induced charge interactions when the craft separation is within three craft radii, including differential charge distribution on a single craft. This can then be expanded to the use of electrostatic sensors and implementation and potential docking applications using Coulomb forces. It allows testing of charge control methods and electronics as well as exploration of the technical challenges of constructing vehicles which can servo their electrostatic potential without causing electrostatic discharges across their components. Vehicle charge densities, including material properties and selection can be studied.

The first generation charged relative motion testbed discussed in this paper is a proof of concept which demonstrates electrostatic actuation capability and provides functionality to conduct experiments simulating fundamental, but simplified CFF applications. The test bed does not simulate the complete operating environment of space, nor allow complete orbital motion simulations. This is a preliminary 1D testbed to develop the application of Coulomb thrust relative motion.

A primary difference between the atmospheric environment and the space plasma environment is the method of charging the vehicle. In the space plasma environment a potential across a small filament can be used to eject ions.[3] However, such charge emission methods are not feasible in atmospheric conditions due to the filament oxidizing within less than a second. Instead, the use of an external high-voltage (kilo-volts) and low-current (micro-amps) voltage supply is investigated.

The paper is structured with a discussion into the background of Coulomb force theory and predicted testbed performance figures. This is followed by an overview of the requirements that led to the design of the first testbed described here. Thorough details of the mechanical apparatus that is selected and implemented in the testbed are presented. The paper concludes with the results of disturbance quantification investigations and preliminary Coulomb actuation studies using the testbed.

COULOMB FORCE

A spacecraft in the plasma environment of space encounters a flux of mobile electrons and protons. A spacecraft in Geostationary Orbit (GEO) will naturally charge to potentials in the kilovolt range depending on the environment conditions and the spacecraft material.[4] The CFF concept utilizes and controls the electrostatic potential of each spacecraft to produce a relative force between them. The free-flying charged particles of the surrounding plasma environment partially shield the spacecraft electrostatic force fields from one another. The strength of this shielding is defined by the Debye length λ_d.[25] The Coulomb force $\boldsymbol{F}_{12}$ that is generated between two craft with charges q_1 and q_2 is defined by

$$|\boldsymbol{F}_{12}| = k_c \frac{q_1 q_2}{r_{12}^2} e^{-r_{12}/\lambda_d} \left(1 + \frac{r_{12}}{\lambda_d}\right) \tag{1}$$

where r_{12} is the separation distance and $k_c = 8.99 \times 10^9 \text{ C}^{-2}\text{Nm}^2$ is the Coulomb constant. The shielding from the plasma environment contributes an exponential decay based on the Debye length. An average GEO environment can yield a average Debye length of 200 meters, with a lower limit of 80 meters that can grow as large as 1000 meters.[24] Coulomb thrust is challenging for LEO applications as the Debye length is around 0.1 meters in length.

Operating with dozens of meters separation distance at GEO, the Debye shielding will only have a minimal impact on the charged relative motion. In the atmosphere of the laboratory it is assumed that the shielding or force decay is negligible as the relative separation distances are very small. The purpose of the testbed is to study the primary $1/r^2$ controlled relative motion, as well as induced charge effects if the vehicles are within several craft radii of each other.

The testbed craft utilize a metallic sphere to hold charge. The spheres charge is controlled by varying the voltage which is defined by a linear relationship through

$$q = \frac{V\rho}{k_c} \tag{2}$$

where V is sphere voltage and ρ is sphere radius.

The testbed does not allow full orbital dynamic motion simulations, however restricted 1D motions are feasible. For instance, it is possible to mimic 1D constrained motion like the natural attractive motion two spacecraft will experience when separated in the orbit normal direction. The linearized Clohessy-Wiltshire-Hill's equations[22] shown in Eqs. 3 can be used to develop a reference orbit configuration. They define a satellites motion relative to a circularly orbiting reference point. The spacecraft position $\boldsymbol{\rho}_i$ is defined by the cartesian x, y and z coordinates relative to the rotating Hill frame $\{\hat{\boldsymbol{o}}_r, \hat{\boldsymbol{o}}_\theta, \hat{\boldsymbol{o}}_h\}$ with orbit radial, velocity and normal directions respectively. With a formation of N spacecraft each using Coulomb thrusting the CW Hill equations of the i^{th} spacecraft relative to the orbit reference is defined by[22]

$$\ddot{x}_i - 2\Omega\dot{y}_i - 3\Omega^2 x_i = \frac{k_c}{m_i}\sum_{j=1}^{N}\frac{(x_i - x_j)}{|\boldsymbol{\rho}_i - \boldsymbol{\rho}_j|^3}q_i q_j e^{-r_{12}/\lambda_d}\left(1 + \frac{r_{12}}{\lambda_d}\right) j \neq i \tag{3a}$$

$$\ddot{y}_i + 2\Omega\dot{x}_i - 3\Omega^2 x_i = \frac{k_c}{m_i}\sum_{j=1}^{N}\frac{(y_i - y_j)}{|\boldsymbol{\rho}_i - \boldsymbol{\rho}_j|^3}q_i q_j e^{-r_{12}/\lambda_d}\left(1 + \frac{r_{12}}{\lambda_d}\right) j \neq i \tag{3b}$$

$$\ddot{z}_i + \Omega^2 z_i = \frac{k_c}{m_i}\sum_{j=1}^{N}\frac{(z_i - z_j)}{|\boldsymbol{\rho}_i - \boldsymbol{\rho}_j|^3}q_i q_j e^{-r_{12}/\lambda_d}\left(1 + \frac{r_{12}}{\lambda_d}\right) j \neq i \tag{3c}$$

where the orbital rate of the reference point (r_c) is defined as $\Omega = \sqrt{GM_e/r_c^3}$, where G is the gravitational constant and M_e is the Earth's mass and m_i is the spacecraft's mass. Ignoring Debye charge shielding and assuming only 2 craft, the one-dimensionally constrained motion along the Hill frame axes are:

$$\ddot{x}_i - 3\Omega^2 x_i = \frac{k_c}{m_i}\frac{q_1 q_2}{(x_i - x_j)^2} \tag{4a}$$

$$\ddot{y}_i = \frac{k_c}{m_i}\frac{q_1 q_2}{(y_i - y_j)^2} \tag{4b}$$

$$\ddot{z}_i + \Omega^2 z_i = \frac{k_c}{m_i}\frac{q_1 q_2}{(z_i - z_j)^2} \tag{4c}$$

The orbit radial direction contains equilibra where x_i is constant and $q_1 q_2 < 0$, while the out-of-plane direction contains equilibria where z_i are constant and $q_1 q_2 > 0$.[26] The along-track direction is neutral and requires $q_1 q_2 = 0$ to maintain a fixed y_i coordinate. The charged vehicle test bed will be able to simulate such equilibria by inclining the track slightly for the $\hat{\boldsymbol{o}}_r$ and $\hat{\boldsymbol{o}}_h$ directly, and having it level for the $\hat{\boldsymbol{o}}_\theta$ direction. Of these 3 directions, the along track direction is the most challenging to implement due to it needing to be as flat and level as possible. The other 2 options are simpler to implement since any unevenness of the track can be exploited to provide the slight gravitation pull or repulsion to simulate this charged axial orbital motion.

TESTBED PROSPECTS AND REQUIREMENTS

With successful Coulomb motion actuation the testbed has fulfilled the proof of concept of safely utilizing Coulomb forces to control a vehicles motion in a terrestrial environment. The potential for Coulomb studies using this testbed and its future derivatives are extensive. Envisioned studies include more complex algorithms for cart position control with a single vehicle. With an extended track multiple carts can be controlled simultaneously, with emphasis on separation distance control, collision avoidance and soft docking.

The testbed has proven the development of preliminary hardware for Coulomb control in an atmospheric environment. It is anticipated that knowledge learnt in this development can be used to further expand technology for future applications in a vacuum situation. The testbed will also allow studies of varying craft shapes, sizes and materials as well as expand the potential of a tethered Coulomb structure.

Using the experience developed in the construction and test of this 1D Coulomb actuation hardware another potential advancement is to extend the principle to a 2D frictionless environment. This can allow multiple craft to be charged and controlled in a formation simulation similar to in plane motion of orbiting spacecraft.

In order to design this first generation testbed, formal requirements were generated and Listed in Table 1. Specifications include hardware aspects, performance and desired outcomes and are explained in further detail in the paper.

Table 1. First generation testbed design requirements

1D frictionless track
Independent hover capability of multiple craft
Track length scalable
All encompassing safety cage and procedures
Electrostatic charging mechanisms and control
Accurate position sensing and logging
Charge polarity switching < 1 s
Accelerations ≈ 5 mm/s^2
Disturbance characterization and mitigation
Study and quantify induced electrostatic effects
Simulate restricted 1D equilibrium configurations

The desired acceleration of the cart on the testbed is faster than that anticipated by a Coulomb controlled spacecraft in GEO, where Coulomb thrust implementation is envisioned. In this operating scenario it is anticipated that maneuvers will occur over time scales of hours and days, with charge polarity switching requiring minutes. The testbed must over come significant disturbances so it is necessary to increase the acceleration of the craft (around 5 mm/s^2) and consequently the desired Coulomb forces.

Test profiles on the testbed will have performance characteristics similar to those shown in Figure 2 which illustrates the expected Coulomb forces and accelerations as a function of separation distance. This is a static force calculation for a cart of 0.5 kg mass using spheres of 25 cm diameter and varying the electrostatic potential from 15 kV to 30 kV. The resulting charged relative motion will experience accelerations on the order of mm/s^2. As a result, any charge feedback control strategy will only need to change the voltage polarity in under a second, and the amount of current being transported to and from the craft is only μA. The resulting Coulomb force for a cart of this size is less than 5 mN.

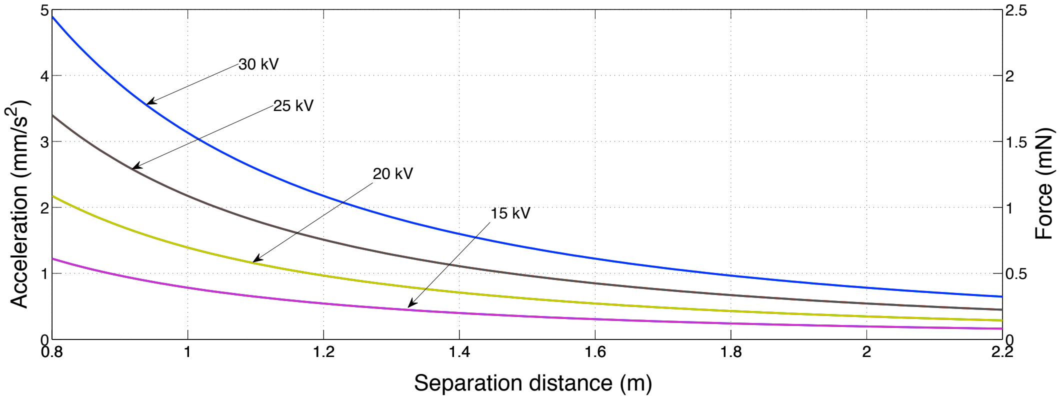

Figure 2 Anticipated Coulomb force and vehicle acceleration for a 0.5 kg cart, spheres of diameter 25 cm voltages of 15-30 kV.

HARDWARE APPARATUS

The goal of this paper is to document and highlight the challenges overcome in developing the Coulomb actuation testbed. The testbed described in this paper is a generic hardware platform that is used to demonstrate and develop aspects of the CFF concept. The current testbed developments are the first version of an envisioned Coulomb testbed suite to answer a number of research questions. The apparatus is under development in the Autonomous Vehicle Systems (AVS) laboratory at the University of Colorado at Boulder.

The hardware apparatus consists of a non-conducting hover track, illustrated in Figure 3, which levitates a charged craft on an air cushion. A second stationary craft is also charged and necessary to create the desired Coulomb force to control the relative motion. Both the fixed body and the vehicle have a 25 cm diameter sphere covered in metal to conduct and hold the electrostatic charge. Each of these spherical nodes is connected to a polarity switching electrostatic power supply capable of $\pm$30 kV and a maximum current of 300 μA with polarity reversal $<$ 1 sec.

The Coulomb forces generated from the charged bodies are relatively small ($<$ 5 mN), so it is imperative that the external disturbance forces are kept to a minimum and the electrostatics dominate. The entire track and all apparatus within a range of 75 cm from the charged spheres are constructed with non-conducting plastic components. This ensures there is no discharge from the spheres and that there are no secondary charged items in the vicinity of the spheres that could induce electrostatic disturbance forces. The dielectric breakdown strength of air is approximately 30 kV/cm which indicates that the possible arc distance from one of the spheres, at full potential (30 kV), is around a centimeter.[27]

Track and cart design

The track provides a level and straight surface to direct the cart motion in 1D with close to zero friction. Commercial frictionless tracks were investigated. However they did not meet fundamental criteria for Coulomb motion testing. Typical air-bearing frictionless tracks are manufactured from metals, typically aluminum. A track such as this is not suitable as it will conduct and can hold charge that will induce undesired external electrostatic disturbance forces. Air bearing tracks also expelled air along the length of the track which is a undesired characteristic as explained in a following section. Plastic track and cart sets were also sourced, however the bearing systems are metal and

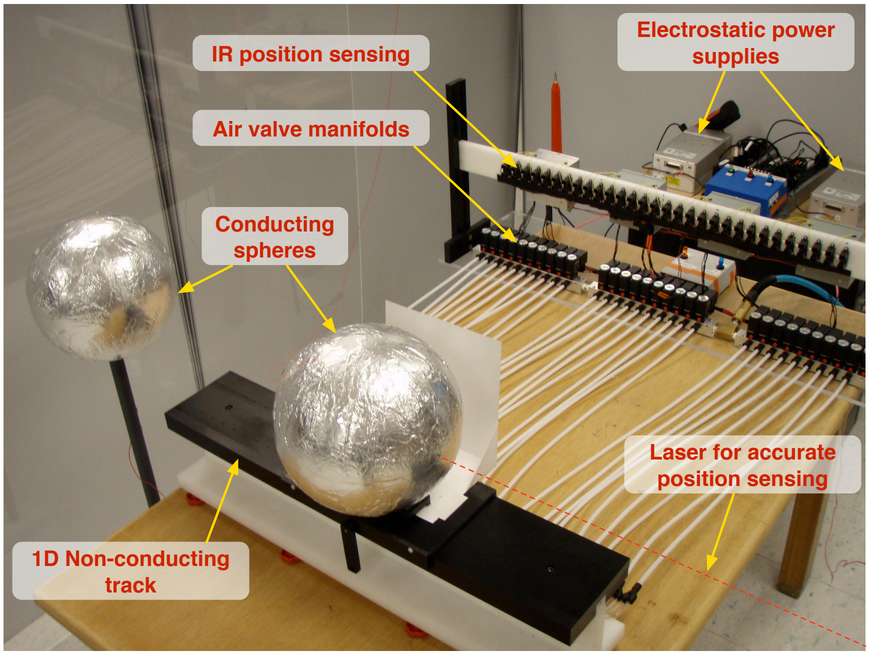

Figure 3. Model of laboratory Coulomb testbed

have friction that can be a magnitude greater than the Coulomb forces of this testbed.

A suitable track was designed and constructed at the University to meet the Coulomb testing needs. It is a square plastic track and cart system that utilizes controllable air flow along its length providing a cushion of air between track and cart achieving near frictionless motion. Along its length it has two rows of air holes on the top and another row along each side. The air holes along the side provide a cushion of air for lateral stability and ensure no contact in any axis between cart and track. A square track was utilized as it can be easily machined and manufactured to the tolerances required. The track design specifications are highlighted in Table 2.

The first track material investigated was the glass fiber weave, G-10. This option was not pursued as machining of the material is difficult and requires additional safety requirements for the airborne glass fibers. The raw material cost is also very high for the amount of stock required in this testbed. The first prototype track was constructed of anti-static Ultra High Molecular Weight (UHMW) polyethylene. This polyethylene compound has a carbon powder added to its composition to dissipate any electrostatic charge build up. The anti-static UHMW provides a suitable prototype material for constructing a track of this length and a smooth machined top surface was achieved. This material however does not maintain dimensional stability and significant warping and deformation is encountered over time.

The current track is constructed of Polyoxymethylene, which is commonly known as Delrin. Delrin was selected as it is easily machined to the tolerances and surface finishes required for the track and with stock this large it maintains dimensional stability. The track is supported with a plastic I-beam made of two pieces of high density polyethylene which is inexpensive, easy to machine and provides suitable rigidity and support. The I-beam design was selected as it provides good lateral support to the track, does not interfere with track air hole design and allows the air connection hoses to be easily connected on the bottom side of the track. The first generation track with cart is shown in Fig. 4

The track is fixed to the I-beam along its length with plastic screws and does provide small variations in track level to be achieved. The overall track level can be easily adjusted by screwing the fine pitch thumb screw feet on the I-beam base. The current track can be held close to level with a measured variation of $< 0.1°$ along its length, which corresponds to a max force of 8.5 mN for a 0.5 kg cart. This is an undesirably high disturbance force, that has been verified with test results, and will be improved on future tracks, however current tests are being conducted on more level sections of the track. In order to maintain disturbances forces < 5 mN it is necessary to maintain a track with level variation $< 0.058°$ for a 0.5 kg cart.

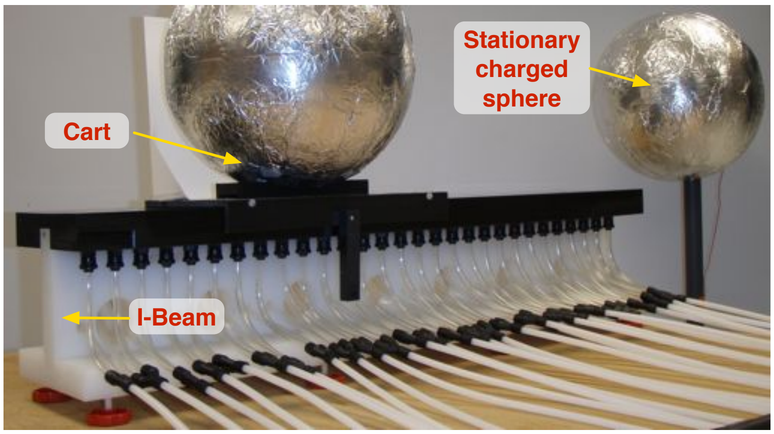

Figure 4. First generation 1D track

The cart itself is manufactured from flat pieces of antistatic UHMW that are fastened together with plastic screws. This provided a light-weight design that had suitable structural rigidity to maintain shape and not hold a static charge that could interfere with the Coulomb forces. The first series of carts were machined from a solid plastic piece, however this proved unsuitable as the desired thin plastic walls warped and caused uneven carts and contact with the track.

Initial testing indicated that small variations in mass distribution on the cart caused undesirable gravitational and air flow forces to accelerate and apply torque to the cart. In a similar principle to a unstable water or air borne craft, it is necessary to have the center of mass below the center of pressure for stability. For this reason, extension rods were added to the cart to investigate cart motion with a lower center of mass. The current cart used in testing has a total mass of 498 grams with conducting sphere, attachments and IR reflecting plate. Cart design specifications are highlighted in Table 2.

Air flow control

The air is supplied to the track through plastic tubing that is connected with plastic push-to-connect fittings. Each segment of air holes along the length of the track is supplied through an individual micro-solenoid valve. This allows the air flow to be controlled along the length of track. Air flow is supplied only underneath the cart for three primary reasons. It is found that a small flow of air in front of a moving cart produces a disturbance force that can prohibit the motion of a cart as it approaches and the opposite effect as it departs. It is also anticipated that future tracks will be an extension in length of this one to a much larger scale and airflow only underneath the

Table 2. Track and Cart specifications

Specification	Value
Track length	76 cm
Track hole separation	2.54 cm
Track width	14.6 cm
Cart length	26.67 cm
Cart wall thickness	0.635 cm
Cart total mass	0.5 kg

cart(s) reduces the overall flow and pressure requirements. Further, while the first generation of tests are operating in atmospheric conditions and along one-dimension only, future generations will investigate 2-dimensional motion, as well as performing tests in a vacuum chamber. This minimal-air track is simpler to scale the testbed concepts to larger tracks and 2-dimensional designs.

The air flow to the track is autonomously operated by remote infrared (IR) sensors that monitor the position of the vehicle, and provide air only underneath it. This system has to be completely unobtrusive in a physical and electrostatic sense. It is also desired that it be inexpensive and not require feedback through a central computer, simplifying the system in many ways. This isolates the system away from the track and removes the requirements to have a large array of data acquisition hardware and digitization.

Alternate sensing methods such as inductance and magnetic sensing was discounted as it requires close proximity and metal objects. A laser is currently used for precise position measurement, however this can only monitor one cart on the track and utilizes a digital signal. The autonomous position system currently uses an array of inexpensive IR sensors, with one sensor corresponding to each track segment and its corresponding valve. Figure 5 illustrates the IR sensor array and electronics connected to the air valve manifold system.

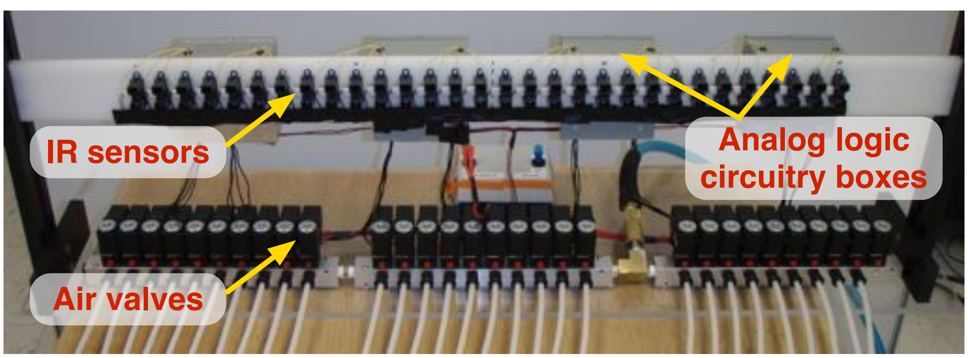

Figure 5. Autonomous air flow control system with IR sensors and air valves

The IR sensors are positioned 75 cm from the cart to not introduce any electrostatic interference. At this range they project a sensing area that is less than 2.54 cm wide and voltage signal of $\approx$ 0-1V depending on cart reflection or not. This voltage signal is then used to drive the valve on/off logic through a comparator circuit with a variable threshold setting. The circuit, as shown in Fig. 6 also features an analog low pass filter and is encased in shielded boxes directly behind the IR sensors to reduce noise and obtain a clean signal for airflow triggering. The whole position sensing and air flow control is completely analog and self sufficient. This stand alone architecture can be easily scaled to a track of any length.

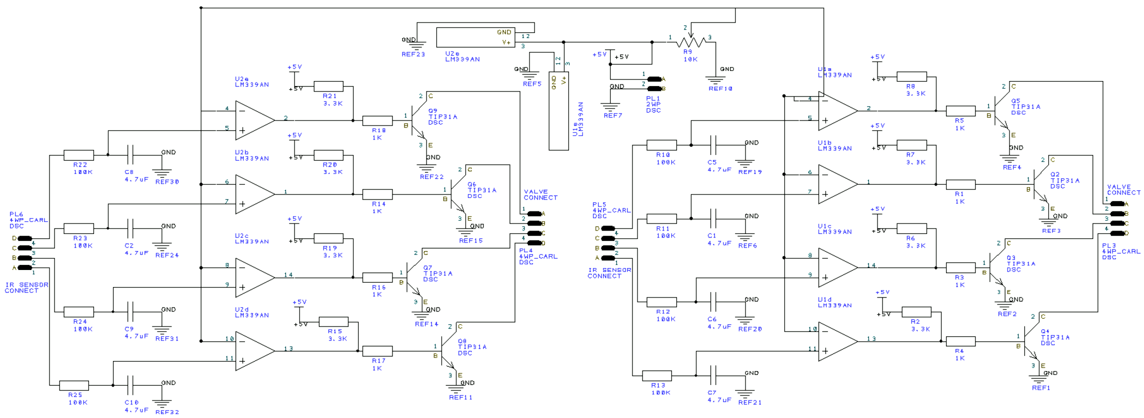

Figure 6. Air flow control electronics circuit diagram

The IR sensors are sensitive and provide a cleaner signal with a flat reflective surface. The cart has a paper reflective sheet that extends beyond the sphere and is used to directly reflect the IR signal. This reflective sheet is a smaller dimension than the cart length so that the cart overlaps the air holes prior to them being turned on. It was found that random erroneous signals were reflecting from the plastic safety cage that surrounds the entire apparatus when orientated in a direct reflection path. To overcome this the safety cage is aligned so that the IR beams reflected at an angle away from their receptors.

Electrostatic power supplies

The charge used for Coulomb induced motion is obtained by two electrostatic power supplies from Spellman High Voltage*. Each bench-top unit is capable of supplying ±30 kV up to 300 μA. This current is more than sufficient for Coulomb testing as the charge needed is a product of high voltage at low current (electrostatics). A primary advantage of the electrostatic power supply is its ability to easily switch polarity offering the full ±30 kV range, allowing a total potential difference of 60 kV between cart and the stationary sphere. As the charge spheres are essentially an open ended circuit with very small load the switching time of the charge polarity is measured to be on the order of ms. Formation control strategies in GEO will require switching well above this limit, on the order of minutes.

The power supply is externally controlled through a standard D-Sub 25 pin interface to a computer. The connection is made through a National Instruments data acquisition card that runs on PCI express architecture. The supplies are monitored and controlled through a custom GUI in Labview as shown in Fig. 7. Power outputs and fault protections are monitored and the voltage level and polarity of each unit are manually controlled. This external controllability easily allows 1D constrained simulations to be implemented.

External power is provided through a control box for user operation and additional safety. Position feedback control algorithms could be implemented on this Labview controlled system. How-

*www.spellmanhv.com

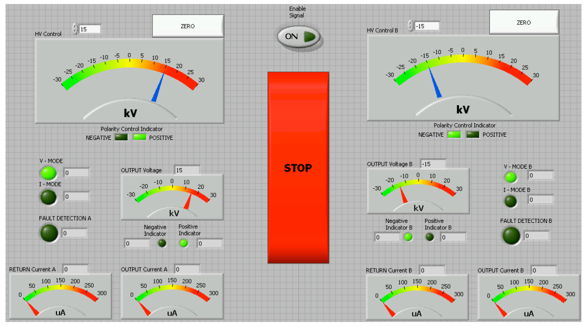

Figure 7. Labview GUI

ever, future versions will be run and controlled in a C-code environment for universal adaptability.

Charged spheres

The electrostatic power supplies are directly connected to spheres that hold the charge used to generate the Coulomb forces. Spheres are an appropriate shape to use for testing as they provide the largest charge density for their size/volume/mass.

The electrostatic power supplies initially drive the voltage to the required level and then use very little power to overcome low atmospheric discharge to maintain sphere voltage. To maximize charge it is desirable to have a large sphere and a high voltage as defined in Eq. 2. The voltage is limited by what is safely operated and feasibly obtainable by affordable laboratory power supplies. The radius of the sphere is limited by the physical size and mass of the cart.

The current cart utilizes a 25 cm diameter hollow styrofoam ball that is covered in a film of aluminum foil. This is of suitable size and mass that appropriately fits on the current cart and track length. The aluminum provides the metallic surface that conducts and distributes the charge necessary for Coulomb interaction.

A voltage dividing probe connected to a voltmeter is used to externally monitor the voltage of the spheres during and after testing. An electrostatic field meter is also desired to measure the field around and in between the spheres. This will improve the calculation of electrostatic charges being achieved and also allow measurement of induced charges and interfering electric fields from surrounding apparatus.

External position sensing

The primary goal of the testbed is to use Coulomb forces to induce motion. The verification of this experiment is to predict cart acceleration and compare to measurements on the track. For accurate acceleration measurements a class 2 laser is positioned along the track length during testing. The position of the cart can be monitored to the sub millimeter level and sampled at up to 50 Hz. The laser has a visible beam and is safe to use in the lab without eye protection. This particular setup will only allow for accurate measurement of one cart. Future test beds with multiple craft will have to incorporate additional sensing devices.

Disturbances

The cart sits on a cushion of air on the track to achieve near-zero friction during motion. however there are still disturbances that are being quantified and minimized. It is imperative that the Coulomb forces, whilst small (< 5 mN), will be the dominant force causing the cart to accelerate. There is no contact friction between cart and track surfaces, except the flow of air between. The major sources of interference that must be addressed include drag from connecting electronics, external charge interaction and an un-level track and other mass/gravity inequalities. Disturbance from the air supply that levitates the cart is also a source of disturbance.

Currently the high voltage lead to the cart is a 36 AWG (American wire gauge) insulated cable that hangs from a supporting rod 1 meter above the track. There is sufficient slack to allow movement along the full track length, so this disturbance can be considered extremely small. The charged spheres are isolated with anti-static plastic and there are no metallic objects within 75 cm of the track and spheres, so the interference from external charge is negligible.

Testing results quantify small track angle offsets lead to undesired gravitational accelerations. Simple offsets in the position of the sphere on the cart result in a weight imbalance and an angled cart causing deflected airflow and disturbance acceleration. These errors are compensated through accurate track leveling and calibration of the cart to the track.

The air flow itself is another error contributor. Due to the inherent analog noise of the simple and inexpensive IR sensors the signal switching of the air valves can have chatter that disrupts the cart. A longer cart spanning greater than 25.4 cm (10 air holes) is being used to better distribute the airflow, however small vibrations are still witnessed during motion as the valves turn on and off. Attempts to provide equivalent air flow from each hole are underway.

Safety

With proper operating practices the Spellman electrostatic power supplies are inherently safe to humans due to their low power output of only 9 W maximum. However, they do require precaution and safety measures that are implemented in the AVS lab. The spheres are ultimately storing the charge, but with a capacitance of 13.9 pF and a total energy of 0.063 J at 30 kV they are also within safe limits, if used with appropriate safety measures.

All tests are performed under stringent safety measures in the AVS lab. All electrostatic and electrical equipment is safely grounded and uses power limiting fuses. Safety and operating procedures are maintained and used during all preparation and testing. The whole testing apparatus is contained within a 6 foot high plastic safety cage that incorporates ground connections and a grounding wand for any necessary discharge. The testbed is only operated with a minimum of two laboratory personnel present.

TESTING RESULTS

The motivation behind this testbed is to perform experiments demonstrating Coulomb forces can be safely and effectively utilized in the laboratory to control the motion of a cart. Testing results for two cases are presented here, with the first being a disturbance characterization without electrostatic motion. The second are results demonstrating cart motion under Coulomb forces.

Case 1: Gravitational disturbance characterization [No Coulomb Forces]

Prior to testing with Coulomb forces a number of experiments have been conducted to characterize disturbance forces acting on the cart. Figure 8 shows the carts speed profile as it moves along the track, for a variety of initial speeds. Without disturbance forces the speed should remain constant along the track length. It is evident that the speed of the cart for each test increases along the track, plateaus and then slightly decreases. Regardless of initial speed, the profiles are the same, indicating the disturbance is constant. Using laser range measurements it was found that the track does have a slight bow downwards from the ends with the lowest part approximately 35 cm from the end. This validates the data shown, indicating that the change in velocity is due to gravity being introduced as a consequence of the track not being perfectly level. This effect will always be present. Future investigate will focus on minimization of these small uneven sections even further.

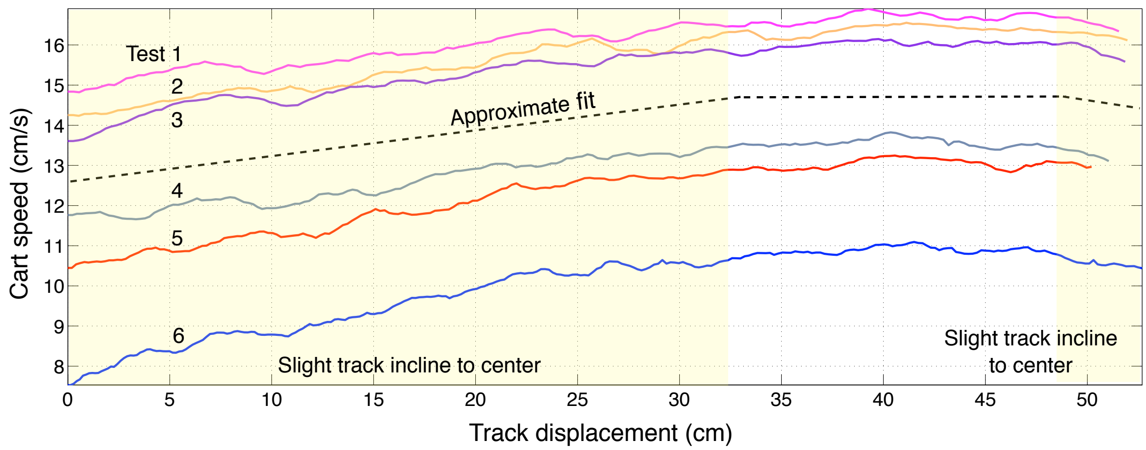

Figure 8. Cart speed as function of track distance (low pass filtered)

Case 2: 30 kV Coulomb repulsion from an initial separation of 76 cm

The simplest level of testing with a single charged cart levitated on the 1D track shows exciting and promising results. The cart successfully accelerates under the influence of Coulomb force. This proof of concept demonstrates the viability of the testbed apparatus and opens a variety of potential CFF studies in the future. There are significant disturbance forces still acting on the cart however it is possible to isolate errors or perform tests with minimal disturbance.

Documented here are the preliminary results of the cart motion tests conducted on a small, but very level section of track with minimal gravitational disturbance. These first test results are a simple single direction acceleration study. The cart is initially stationary at a separation distance of 76 cm between centers. Both spheres are charged to +30 kV and the cart is accelerated away from the stationary sphere under Coulomb force. The test is conducted with the 0.5 kg cart that has an even mass distribution.

The results of two cases of this repulsion test are displayed in Figure 9. The Coulomb force displacement due to the ideal vacuum electrostatic force in Eq. 5 is also shown in Figure 9 based on the same initial separation distance and stationary start as those measured of the actual cart.

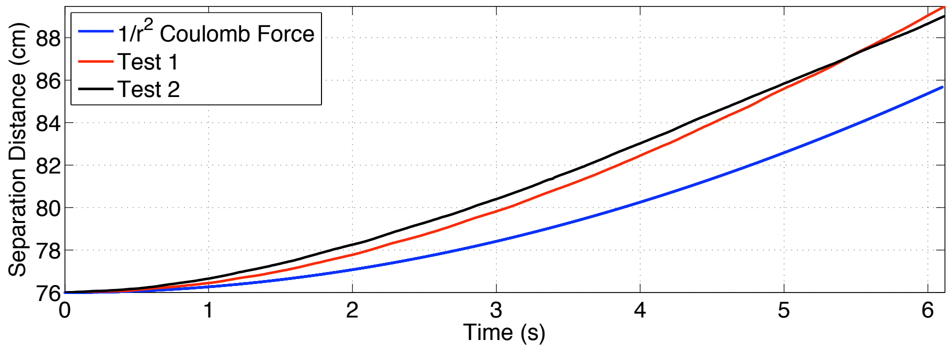

Figure 9 Coulomb acceleration tests conducted with a cart initially at rest and repulsed with +30 kV potentials on both spheres

$$\boldsymbol{F}_c = \frac{|V_1 V_2| \rho^2}{k_c r_{12}^2} \tag{5}$$

Case 3: 30 kV Coulomb attraction from an initial separation of 94 cm

This test case demonstrates the Coulomb attractive force capabilities. The cart is initially stationary at a separation distance of 94 cm between centers. One sphere is charged to +30 kV, while the other is charged to -30 kV, which accelerates the cart toward the stationary sphere. The test is conducted with the equivalent 0.5 kg cart and begins on the flattest section of track.

The results of two cases of this attraction test are displayed in Figure 10. Once again the data is compared to the Coulomb force displacement due to the ideal vacuum electrostatic force as given in Eq. 5, using the same initial separation distance and stationary start as those measured of the actual cart.

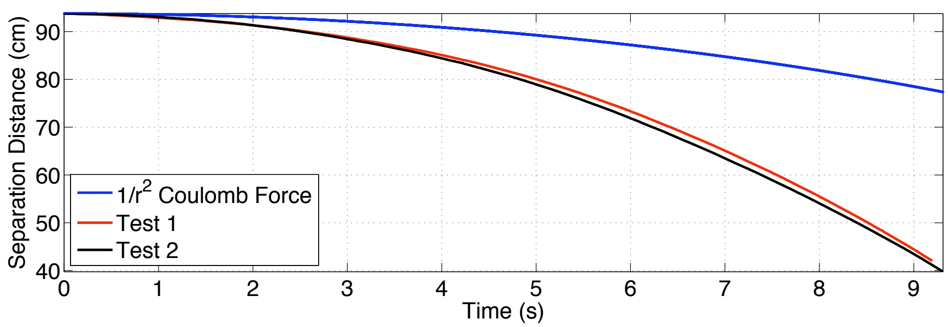

Figure 10 Coulomb attraction tests conducted with a cart initially at rest and attracted with cart at +30 kV and stationary sphere at -30 kV

There is a clear discrepancy between the test data and the ideal vacuum electrostatic force. Accelerations higher than the point charge electrostatic response are recorded. This is a consequence of induced charge effects causing an additional attractive force as the spheres become close. This was confirmed by obtaining acceleration data from a cart with only induced charge forces acting (Only one sphere charged).

These preliminary tests illustrate that the test bed can be used to safely perform electrostatically actuated vehicle relative motion experiments. The induced charge effects can be challenging to model analytically or numerically. Even this first generation testbed has already demonstrated this phenomena. This is particularly useful to investigate charged docking concepts where the craft will be within three craft radii of each-other.

CONCLUSIONS

This paper documents the progress made on a first generation testbed intended for preliminary spacecraft Coulomb control studies. A one dimensional air bearing track is used to levitate a cart that can be safely actuated by electrostatic (Coulomb) forces. The technical challenges in developing this frictionless motion track are described in detail. The findings indicate that implementation of electrostatic charge devices and the methods of controlling and monitoring this hardware is feasible.

Preliminary results characterizing known disturbances as well as the testbeds actuation capabilities are presented and indicate that gravitational forces are prevalent. Complete 1D motion testing of the charged vehicle is conducted and analyzed. The vehicle testbed is successfully used for both attractive and repulsive maneuvers with results shown.

The construction and preliminary results of this testbed indicate that there is a wealth of knowledge that can be obtained that benefits the development of the Coulomb formation flight concept. There are numerous aspects of this first generation testbed that can be further investigated and improved upon for future applications. Significant focus on disturbance quantification and mitigation will be performed as well as investigations into secondary effects such as induced charge.

The development of this testbed and the associated studies are a vital step in the progression of the Coulomb controlled spacecraft formations concept. The Coulomb controlled spacecraft concept is an application of current technologies that offers precise separation control, without plume impingement concerns and for very low propellant mass. The concept can be used for soft-docking, deployment and tether applications. The development of this testbed for Coulomb thrust is a integral step in taking the concept to space that may revolutionize spacecraft formation flying control.

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