PARACHUTE DYNAMICS INVESTIGATIONS USING A SENSOR PACKAGE AIRDROPPED FROM A SMALL-SCALE AIRPLANE

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ABSTRACT

We explore the utility of various sensors by recovering parachute-probe dynamics information from a package released from a small-scale, remote-controlled airplane. The airdrops aid in the development of datasets for the exploration of planetary probe trajectory recovery algorithms, supplementing data collected from instrumented, full-scale tests and computer models.

1. INTRODUCTION

A probe-parachute system descending through a planetary atmosphere will encounter attitude motions, both due to intrinsic stability properties of the parachute and probe, and in response to wind shear. These motions must be understood, both to predict the dynamic environment which provides a context for other sensing (e.g. imaging or radar altimetry) and to permit the reconstruction of winds from on-board dynamic measurements. Attitude dynamics models e.g. [1] require experimental validation: however, full-scale tests with stratospheric balloon drops etc. pose enormous logistical difficulties and entail substantial costs [2]. We explore here what can be learned with small-scale parachute probes, since the dynamics instrumentation can now be miniaturized.

Parachute-probe drop tests of this type were previously conducted by hand-dropping small-scale sensor packages from within the atrium of the Lunar and Planetary Laboratory at the University of Arizona [3]. This testing environment was well controlled, less the modest influence of the ventilation system, but the data collection periods were very limited. The transient effects of the launch and parachute inflation left little time for data to be collected before reaching ground level, even at low descent speeds. However, this first drop test did help build a dataset of attitude motion to gain familiarity with sensor data and corresponding motions. While the drop tests focussed on low-cost and ease of use, rather than dynamic similarity, they provided the starting point for the development of a simple parachute-probe model [1]. Even more importantly, the indoor drop tests proved the usefulness of combining simple testing procedures with inexpensive electronics to explore parachute dynamics.

With a general understanding of parachute dynamics from the indoor tests, a new series of probes and alternate testing procedure was developed (See Fig. 1). This new test series aims to increase the data collection time and attempt to identify characteristics of specific parachute designs by testing a variety of parachute types such as flat, spherical, cross, and disk gap band.

Fig. 1. The two versions of the parachute-probe dynamics test-beds with a pencil for size reference. The preliminary version, shown on the right, was soon replaced with the larger version, on left, to better support the growing sensor package.

A series of Basic-X 24 micro-controllers are used to collect data from the onboard sensors. In addition, airdrops are documented with ground-based video cameras in order to document the general behaviour of the parachute-probe system for comparison with onboard sensor data.

The parachute-probe system utilizes two main sensors packages for data collection. A tri-axial, six-degree of freedom inertial measurement unit (IMU) by O-Navi provides angular rate and acceleration. The magnetic field is determined from an orthogonal triad of FGM-1 fluxgate magnetometers. Attempts were made to supplement the main sensor packages with a pressure sensor, a Global Positioning System (GPS) and a camera and processor developed by the Robotics Institute at Carnegie Mellon University (CMU), but with little success.

The airdrop tests utilize a series of parachutes manufactured for model rocket recovery. A small-scale, remote-controlled airplane is used to ferry the parachute-probe sensor package to altitudes permitting adequate descent durations. During the airplane's ascent, the probe and folded parachute are secured underneath the fuselage of the plane by rubber bands. When the desired altitude is reached, a command is sent from the pilot to release the parachute-probe package. Each data collection is initiated when the probe is separated from the bottom of the fuselage. At this time, the sensors are polled for a specified period of time and the data is stored in the EEPROM of the onboard micro controllers. After the data collection period has expired each of the onboard controllers continuously reads out the EEPROM data to a serial port until power is reset.

2.   PROBE INSTRUMENTATION

The original probe design aimed to gather information about the general behaviour of parachute descent dynamics from a wide variety of sensors (see Table 1 for an approximate cost for each component). However, some sensors proved more reliable and better suited for our application than others.

2.1 Micro Controller

A series of BasicX-24 micro controllers manufactured by Net Media were used to collect and store sensor data during the parachute drops. The BX-24 is a 24-pin package containing an ATMEL micro controller running at 65,000 instructions per second, a 32K EEPROM, clock and power regulation and serial port components. As a standalone unit

powered by a single 9V battery and programmed in a Basic language it can perform a range of data acquisition, communication and control tasks. We use it simply as a convenient data logger: the controller has 8 on-board 10-bit A/D converters and enough EEPROM space to store data for a usefully-long flight. (The Basic Stamp units we used previously [3], while easier to use and more robust, lack the A/D converters, run slower, and have less EEPROM space, for the same cost).

One issue we encountered with the BX-24 is that a crystal oscillator, mounted a little above the package circuit board, sheared off during some of our early tests when high impact loads were encountered. High impact loads were experienced when a significantly heavier instrumentation package was tested with an older version of the parachute-probe attachment mechanism. The more massive probe applied larger stresses on the attachment mechanism than expected, and the attachment failed during probe deployment from the ferry airplane, allowing the probe to plummet to the ground without a parachute. Rapid deceleration at ground level caused the crystals to shear off three of the four micro controllers. The attachment mechanism was upgraded with stronger metal and additional adhesive was applied to support and secure the crystal during future drops.

2.2 Primary Sensors

The Gyrocube IMU and the triad of fluxgate magnetometers provided the backbone for our data collection.

The sensor outputs (analog voltage from the Onavi, and digital pulse rate from the magnetometers) are recorded by the micro controller, scaled to an integer 0-255 and written to the controller's on-board EEPROM as 1 byte for each sample. After the flight, the EEPROM data is read out to a serial port: the data is captured by a terminal program running on a laptop computer to which the package is connected by cable. We have used similar methods in our earlier drops [3]. Construction details for similar equipment, used to measure flight dynamics of Frisbees are given in [4].

The IMU and magnetometers proved to be the most reliable sensor, as long as the probe battery voltage was monitored regularly. The monitoring of battery voltage after each drop proved important for two reasons. First, even with equipment to assist in finding the probe after landing, the probe occasionally encountered thermals that forced us on mile-long treks through the desert to retrieve the probe. Second, even when strange weather did not carry the probe miles away, the downloading of the data stored on the micro controllers took time. The

combination of long retrieval and download times and sloppy battery monitoring can drain the onboard batteries, forcing partial or full data loss. Once aware of these concerns, batteries were monitored more closely and replace often, and afternoon drops were avoided as much as possible.

2.3 Ancillary Sensors

A Global Positioning System (GPS) designed to track model rockets was added to the bottom shelf of the probe in an attempt to provide ancillary information during each drop. GPS Flight's STXe GPS receiver and radio modem and RXB2 base station receiver unit operated completely independent of the other probe sensors. Position and velocity data were transmitted directly to the ground station, while other sensor data was recorded to the micro controllers. The GPS position and velocity data was intended to be used to determine the horizontal translation, descent rate, and the approximate probe-landing site. In spite of these goals, and the ease of integrating the small receiver and radio modem into the existing probe setup, the addition of the GPS did not work as planned. The GPS antenna was mounted on the top of the probe in order to receive information from orbiting satellites during the drop. However, when the probe was mounted on the bottom of the aircraft this antenna was pointed horizontally and further attenuated by the fuselage, causing complete loss of satellite signal. This loss of signal remained through the ascent onboard the aircraft and during a majority of the drop sequence. Multiple antenna locations and probe mounting arrangements were attempted, but with little success. Future integration of a higher-quality antenna may yield better results.

A camera and processor developed by the Robotics Institute at Carnegie Mellon University (CMU) was hoped to be a novel feature of our probe airdrop tests [5]. The CMUcam was designed to provide a low-cost approach to onboard, real-time vision processing for mobile robots. The CMUcam can be programmed to track the position and size of an object that is of high contrast to its environment. For our application the camera and accompanying processor are used to track the position of the marker object in the interior of the parachute canopy in order to determine the parachute's motion relative to the probe. The small camera and processor board is mounted on the inside of the probe and the lens is directed toward the open parachute canopy. A rectangular marker made of thin paper, and of contrasting color to the parachute, is secured to the center of the canopy interior. A BasicX micro controller is wired to the CMUcam and instructs the CMUcam to capture and analyze an image for the colored marker by sending a "track

color" command. The track color command is specific to the color of interest: the color of the marker inside the parachute canopy. For example, to determine the motion of the flat, orange parachute relative to the probe a black rectangle is used and the command "TC 45 60 22 35 27 45" is sent to the CMUcam. This command specifies the minimum and maximum values for red, green and blue, color of interest that the camera should track, in this case, a shade of black. The CMUcam outputs a string indicating the tracked rectangle's center of mass and corner locations in x and y coordinates, the number of pixels in the tracked region, and a value indicating the confidence the processor has that it has successfully tracked the object. In theory the CMU camera would provide information about the relative motion of the parachute-probe system by tracking the position and size of a colored marker on the inside of the parachute canopy during the decent. Ground tests using Hyperterminal and a JAVA based Graphical User Interface (GUI) provided with the CMUcam kit have yielded promising results. Using the JAVA GUI we have found appropriate maker sizes, shapes and colors that, when placed on a specific parachute, can be tracked well enough to record the spinning and translation of the parachute relative to the probe. Ground tests also revealed the influence of lighting conditions on the quality of the CMUcam tracking. Shadows cast on the chute and changing lighting conditions throughout a days worth of airdrop testing can make the marker less recognizable to the camera. However, these ground tests used Hyperterminal to view and capture the tracking data and in order to use this vision processing technique during a real drop the data must be written to the EEPROM of a micro controller onboard the probe. As of date, attempts to program the BasicX to properly store the CMUcam's string output to EEPROM have been unsuccessful. However, it is hoped that as the probe evolves, our BasicX programming abilities will also, and the CMUcam will one day provide an interesting perspective to parachute dynamics.

Experiments employing, an Omega PX139 pressure sensor to act as an altimeter have so far been unsuccessful.

Table 1. Description and approximate cost of probe instrumentation and components.

Description	Cost
BasicX Micro Controller	$50 (each)
Onavi IMU (+- 2g, +-200 degrees / second)	$510
FGM-1 Magnetometers (+- 0.7 oersted)	$43 (each)
Omega PX139 Pressure Sensor	$85
CMUcam (kit)	$109
108 db Buzzer	$5
PWM Activated Relay	$30

3. PROBE CONSTRUCTION

The outer shells of the probes are made from a plastic cardboard-like material referred to as chloraplast. Chloraplast is commonly used to make temporary signs and displays. The blue chloraplast was scored, folded, and then reinforced with epoxy filled corners to form the strong, lightweight, rectangular cases. The first probe has dimensions 20 x 10 x 8 cm, not including the foam block mounted on the bottom for shock absorbance on landing. When more sensors were added, the second probe (24 x 11 x 9 cm) was constructed and weighed about 800 grams with all sensors and power supplies. The micro controller development boards are mounted on pieces of dense foam and inserted into the probe like shelves, making the probe very modular in design. The foam shelves support the boards and are secured to the chloraplast with 4 screws, providing plug and play abilities. A downside to the multiple shelve design is that the wiring to and from the switches, batteries, micro controllers, etc can be messy and frustrating during maintenance and debugging.

Velcro straps secure the probe door in place allowing quick and easy access to each serial port on the development boards, which are continuously dumping the data stored in their EEPROM. The top of the first probe was made of chloraplast, but after absorbing the force of many deployments from the plane the chloraplast began to give way. The second version featured a hard wood top. A single piece of fishing line loops through four metal eyelets at each corner of the probe and a key ring in the center providing a well-balanced anchor point in the shape of an "X." The fishing line proved to be the strongest and least obstructive to the CMUcam's view of the open parachute canopy.

4. AIRDROP SYSTEM

The main purpose of the airdrop tests was to build a larger data set with increased data collection periods. To accomplish this we constructed an airdrop system that consists of a stable aerial platform, a reliable release mechanism, and a data collection status indicator.

4.1 Airplane Platform

A small-scale, remote-controlled (R/C) airplane called the Xtra-Easy is used to ferry the parachute-probe sensor package to the release altitude. The Extra-Easy airplane is manufactured by Hanger 9, has a wingspan of 1.75 meters and weighs approximately 3 kilograms. This platform was chosen to ferry the probe because it is a very inexpensive, stable platform, designed specifically for the beginner R/C pilot. This simplistic platform provided us with the bare minimum for flight and avoided extra complications that come with aerobatic airplanes and other "bells and whistles" available on small-scale aircraft. All the equipment needed for flight, including the complete airframe, engine, and controller, is available in a "Ready to Fly (RTF)" kit. The RTF kit provides an airframe nearly assembled for flight. Although the airframe is equipped with the standard point forty cubic centimeter motor, it was replaced with an OS .61 FX (point sixty one cubic centimeter) engine to better suit the needs of this project. This engine upgrade allowed the parachute-probe to be carried to the drop altitude with ease and speed, thereby decreasing the time between data collections. The airframe and mounting of the probe are shown in Fig. 2 and Fig. 3.

Fig. 2. The Xtra-Easy airplane taxing to the runway with the probe and parachute securely mounted under the fuselage.

Fig. 3. Upclose view of the first probe under the fuselage with the medium-sized, flat parachute.

4.2 Mounting and Release Mechanism

The probe is mounted underneath the airplane's fuselage and secured in place by a chain of rubber

bands. Both ends of the rubber band chain series are permanently affixed to the plane. The middle rubber band is attached to a metallic loop that is pulled around the probe and slid over a metal rod jutting out from the opposite side of the fuselage. This metal rod is attached to the arm of a servo (a typical actuator used in remote controlled airplanes) that is connected to the same receiver box that the pilot uses to manipulate the control surfaces on the airplane. The metal rod is bent at a slight upward angle so that the loop does not slide off unintentionally before the release signal is sent. The servo is commanded to extend the metal rod outward during ascent, holding the rubber bands in place around the probe. When the pilot activates the servo from the R/C transmitter, the servo pulls the metal rod into the fuselage thereby releasing the parachute-probe system.

Data collected during the plane's ascent is of no interest to us. To ensure that we collect and record data during the descent, and not while the probe is attached to the plane, an "nc switch," or normally closed switch, was implemented on the probe. When the probe is securely mounted on the bottom of the airplane a fuselage-mounted peg depresses a push-button located on the backside of the probe opening or breaking the circuit. When the micro controllers are powered, they are instructed to monitor the status of this push-button. The micro controllers take no action while the button is depressed. When the probe is released from the plane, the peg no longer depresses the switch and the micro controllers begin to sample data from each of the sensor packages.

In preliminary airdrop tests, rough take-offs and awkward mounting of the probe under the plane made us question if the probe had begun collecting data while still attached to the plane. To clarify when data collecting or dumping was taking place we installed a 108-db buzzer and Pulse Width Modulation (PWM) activated relay. With these new components installed, the micro controller is instructed to send a PWM command to the relay to stay open while the probe is attached to the plane, closed when it detaches and collects data, and then alternate between open and closed when full data is collected and is being dumped over the serial port. When the relay is closed it allows the buzzer to sound, indicating that data is being collected. When collection is complete the buzzer pulses on and off. The buzzer and relay were very helpful in determining the status of the data collection and in helping to locate the probe after the drop.

4.3 Parachutes

Parachutes manufactured for model rocket and small Unmanned Aerial Vehicle (UAV) recovery proved

ideal for our airdrop tests. Initial plans called for the testing of four types of parachute including flat, spherical, cross and disk gap band. However, time constraints have limited the research thus far to the use of flat and spherical parachutes shown in Fig. 4. Cross and disk gap band designs are planned for future tests. Specifications of the spherical and flat parachutes used in these tests are listed in Table 2. Each of the Apogee Rockets parachutes used in testing are made of 70-devier rip-stop nylon and the suspension lines are braided nylon. The spherical parachutes are made of comparable ripstop nylon and utilize similar material for suspension lines.
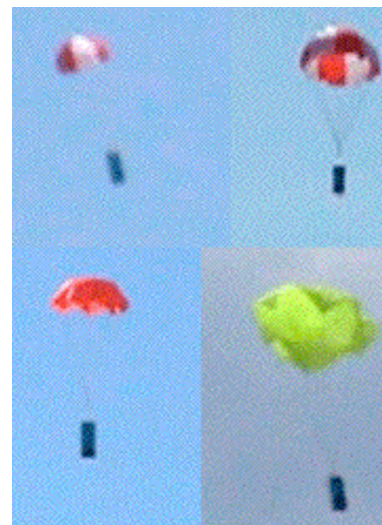

Fig. 4. The four parachutes during drop tests.

Table 2. Parachutes used for testing. The diameter, D, height, H, and suspension line length, L, are given in centimeters. Mass, M is given in grams and includes the suspension lines.

Type (Manufacturer)	D	H	L	Mass
Spherical (Spherachutes)	76	43	79	52
Spherical (Giant Leap)	132	68	112	180
Flat Octagon (Apogee)	99	48	86	65
Flat Octagon (Apogee)	152	76	140	134

5. SET-UP AND TESTING PROCEDURE

5.1 Probe Calibration

Once constructed, the sensors were calibrated by completing a series of controlled maneuvers. A small, spinning table, rotated by a servo and R/C transmitter and receiver, was constructed to calibrate the gyros on the IMU board. The accelerometers were calibrated by   laying the probe on each of its 6

sides. Calibrating the magnetometers proved more difficult but was completed in a similar fashion

5.2 Test Procedure

The drop tests were conducted at the Tucson International Modelplex Park Association (TIMPA), a local remote-controlled flying field. The TIMPA facility provided ample open space and a safe, frequency controlled testing environment for our remote controlled airplane assisted drops.

During the airplane's ascent, the probe and folded parachute are secured underneath the fuselage of the plane by the previously described rubber band arrangement. The elapsed time from take-off to release altitude is less than one minute with the engine upgrade and an experienced pilot. When the desired altitude is reached, the pilot releases the parachute-probe package by retracting the rod supporting the metal loop. The probe separates from the plane and data collection is initiated when the fuselage- mounted peg no longer depresses the trigger switch. At this time, the PWM activated relay sets the buzzer to constant output and the micro controllers begin to poll the sensors for a specified period of time (just over 2 minutes for the magnetometer and IMU boards). Sensor data is stored in the onboard micro-controller's EEPROM and the drop is documented from the ground with a camcorder. Examples of camcorder footage are shown in Fig. 5. After the data collection period has expired the onboard controllers continuously reads out the EEPROM data over a serial port connection while the PWM relay alternates the buzzer signal. Upon touchdown the buzzer is deactivated and the probe is transported to a laptop computer for archiving and analysis. In contrast to real-time data transmission, the storage of data onboard during the descent avoids interruptions to the transmission and allows for more samples per second to be collected. We used a serial cable and the BasicX software to capture the data from each micro controller to files on the laptop.

6. DATA ANALYSIS

A variety of computer programs were constructed using Interactive Data Language to compute, display and compare sensor data and off-board camera footage in order to gain familiarity with the data and corresponding motions of the system and look for possible patterns due to parachute characteristics.

6.1 General Visualization with Camcorder Data

Drops were recorded from the ground in order to document the general behaviour of the probe and

parachute during the descent. The drop sequence shown below is of drop 8 on July 11, 2004, beginning just 9 seconds after release from the plane. The sequence spans a mere 4.5 seconds (the images are 0.14 seconds apart) with one of the parachute lines pulled slightly shorter than the others which caused a conical pendulum motion. However, this sequence clearly shows the parachute-probe spinning clock-wise and then counter clock-wise (follow the folded parachute edge and probe edges through the sequence).
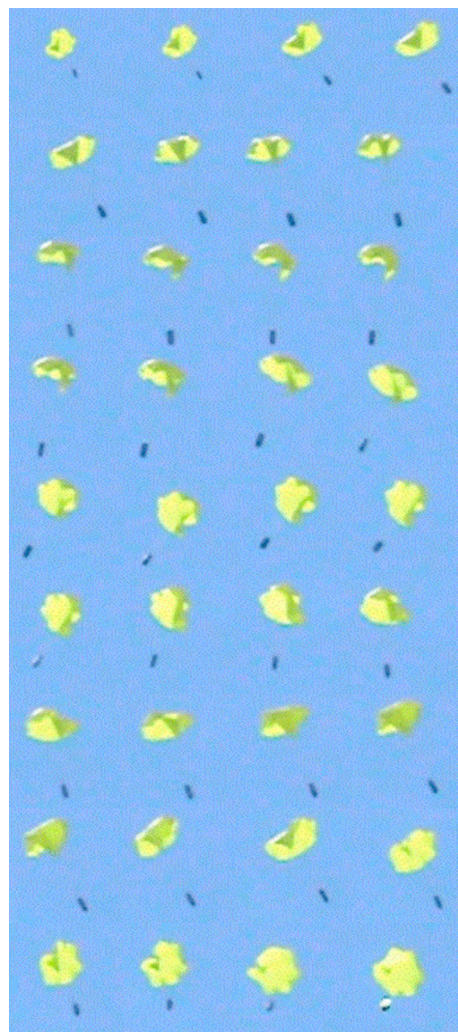

Fig. 5. Ground based imaging of the large, flat parachute during drop 8. One line is tangled causing and edge of the chute to curl over.

6.2 On-board Sensor Data

IMU data recorded for drop 8 are shown in Fig. 6. a,b,c and Fig. 7. a, b, c, respectively.
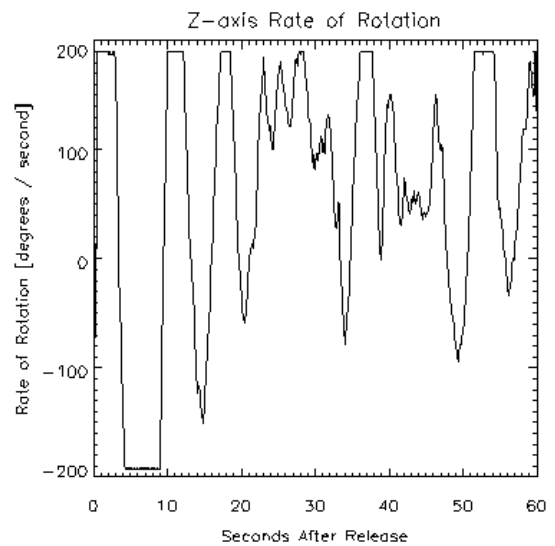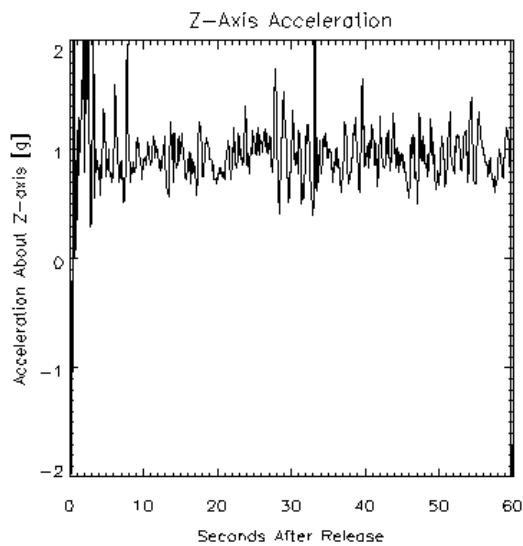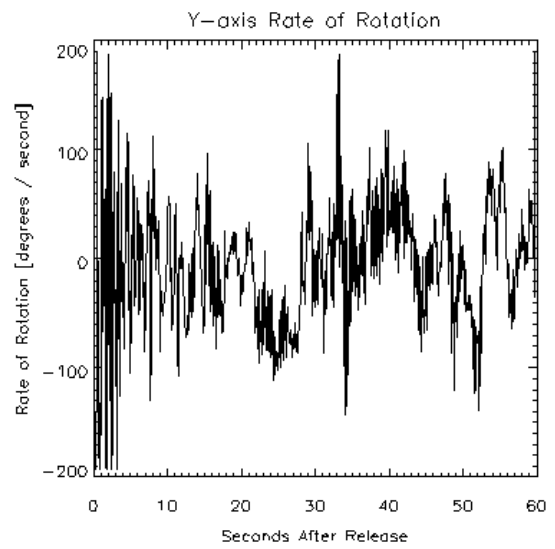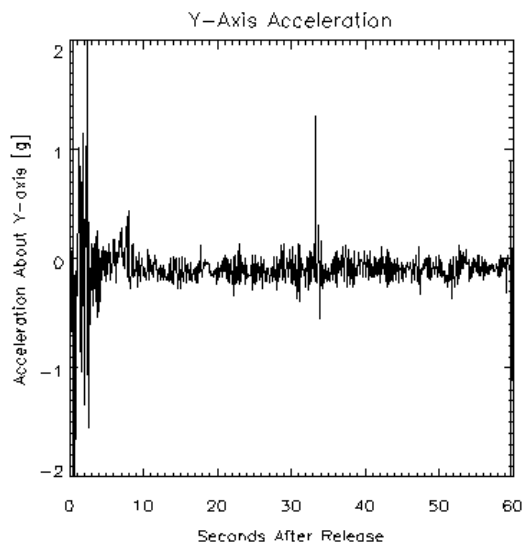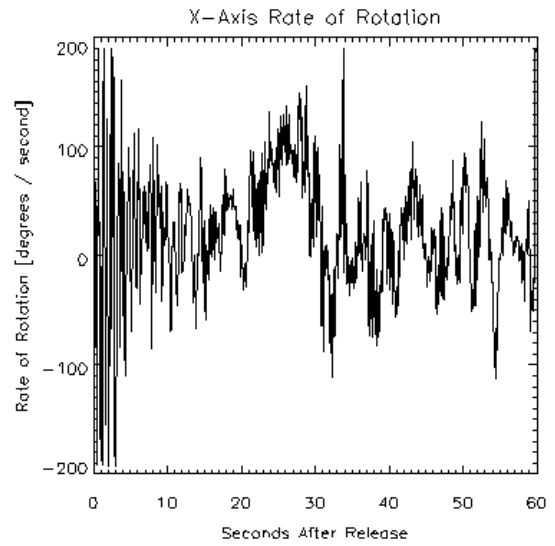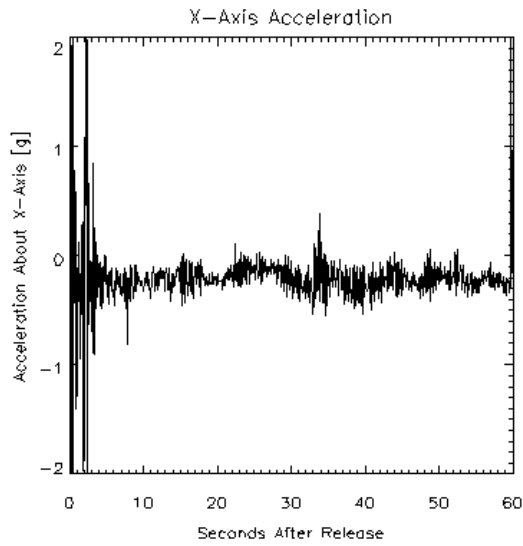
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Fig. 6. a, b, c. X-, y-, and z-axis accelerometer results for drop 8 with the large, flat parachute.

Fig. 7.a,b, and c. X-, y-, and z-axis rate of rotation for drop 8 with the large, flat parachute.

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The same change in rotation shown by following the parachute-probe camera sequence can be seen in the gyro plot, Fig. 7.c. It is difficult to pinpoint the true time during the drop that probe began to change rotation while looking at the image clips, but each change can be identified and matched with changes in rotation from the gyro plots, even if the timing of the two methods are not exactly in sink. Note that the flat parts of the plot are due to the gyro saturation limit of 200 degrees per second. The video record for drop 8, and others, exhibits periods of conical pendulum motion. It was suspected that this behaviour would be accompanied by persistent, rather than periodic, z-axis acceleration values greater than 1 g. Drop 8, and other drops with the flat parachute, have not confirmed this kind of result, but it may be discovered in future analysis when all instances of coning can be more closely examined. In an attempt to quantify the results from the acceleration and gyro data, a computer program was written in IDL, which calculates the mean, standard deviation, skewness, and kurtosis of 10-second segments of the sensor data collected during the drops. The results are then plotted with symbols and colours representing the general size (small, medium, large) and type of parachute (spherical or flat). We aimed to identify patterns in this data that could link the particular parachutes to specific results, but so far our attempts have been unsuccessful. Irregular flight conditions, such as tangled lines, or uncontrollable and changing weather conditions could be the cause to the irregular results. An additional approach to analysing the drop data is the use of Fast Fourier Transforms (FFT). The same, 10 second segments described above are passed through an FFT function that extracts the frequency of the oscillatory acceleration and magnetometer data. An example of how this function is applied to a segment of oscillating x-axis gyro data from drop 11 with the medium, flat parachute is shown below.
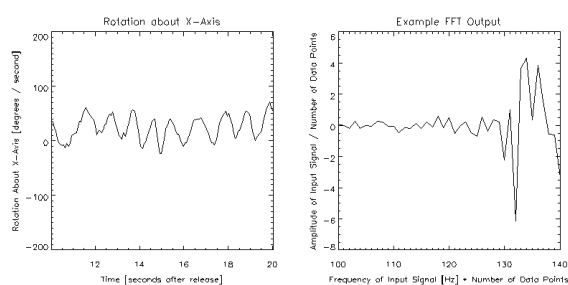

Fig. 8. Example fast Fourier transform application using x-axis gyro data.

The input function shown on the left in Fig. 8 is described with 141 data points and we can approximate the period as 1 second. The FFT command displays a spike at the value corresponding

to the (frequency of the input * the number of data points used to describe the input). In this example, a series of spikes are noted around 135, therefore the FFT has identified the input pattern 0.96 Hz frequency of oscillation, or a period of 1.04 seconds. This method is used with gyro and magnetometer data to calculate the swing period of the parachute-probe system.

7. SUMMARY

Small-scale sensor packages and parachutes were airdropped from a small-scale airplane in order to gain familiarity with the descent kinematics of a planetary probe through an atmosphere and to explore interactions of the parachute system with in-situ measurements. Testing and analysis techniques used to explore the parachute-probe system have been reviewed as well as the discussion of future plans. These experiments have obvious visual appeal and are relatively inexpensive to perform. Additionally, the data acquisition equipment is in fact quite easy to assemble. This research has aided the development of a dataset for use in the evaluation of trajectory recovery algorithms and methodologies.

8. ACKNOWLEDGEMENTS

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