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Open data generation for space debris attitude estimation using glider parabolic flights

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Abstract

Algorithms for Attitude and Orbit Control System (AOCS) and Vision-Based Navigation often need to be fitted and tested on observations of actual tumbling objects in microgravity. However, such data are usually scarce, since access to earthbound microgravity is limited and since their results are usually not made openly available to the community of researchers. The purpose of the Space Tumbling Attitude Data Generation (STAG) project is to provide data on the attitude and motion of tumbling objects in microgravity to support the development of attitude estimation for the next generation of Active Debris Removal mission proposals. An experimental platform was developed to log the motion and attitude of small objects and to compare them with monocular imagery. The experience is designed to fit a glider which can emulate microgravity conditions during parabolic flights. The collected data are being shared openly to enable the investigation of the attitude dynamics of objects with various shapes and inertial properties, and to allow validation of image processing algorithms on recognizing the objects attitude. The dataset is intended to support research on the motion of tumbling objects, providing valuable data for the advancement of space debris removal technologies.

Keywords: microgravity, parabolic flight, tumbling debris, AOCS, glider, open data**.**

Acronyms/Abbreviations

ADR: Active Debris Removal
AOCS: Attitude and Orbit Control System
IMU: Inertial Measurement Unit
STAG: Space Tumbling Attitude Data Generation

1. Introduction

The growing population of space debris poses a significant challenge to the continued safe operation of spacecraft and space infrastructure in Earth's orbit. Accurate determination of the attitude and motion of these non-cooperative tumbling objects in microgravity are crucial for the development of effective space debris removal technologies and the planning of future Active Debris Removal (ADR) mission proposals. The Space Tumbling Attitude Data Generation (STAG) project was initiated with the primary objective of providing data on the attitude and dynamics of tumbling objects.

Different methods have been previously proposed to estimate the attitude and motion of non-cooperative objects in space [1]. A subclass of these methods focuses on the use of monocular imagery as a promising, cost-effective approach [2]. While synthetic images are often being used, the training and validation of these methods could benefit from independent and empirical data [3,4]. However, current availability of such datasets is limited [5]. Additionally, from a theoretical perspective, improving our understanding of the dynamics of tumbling objects is crucial for the design of future ADR missions. This paper introduces an experimental effort to gather more openly accessible data on tumbling objects in microgravity, a step forward in the continued effort to tackle space debris.

To achieve this goal, a simple experimental platform was conceived, designed, and implemented, which utilizes Inertial Measurement Unit (IMU) sensors and monocular image recording. This platform is integrated into a glider, as sailplane gliders have recently been tested as an alternative and low-cost platform for parabolic flights [6,7,8].

In this paper, we present the STAG project, including the experimental procedure, the hardware employed, and details on the collected data. The data generated in this project is made openly accessible from an online repository (see **Data availability** section) and can be used for the validation of attitude estimation and simulation techniques, ultimately contributing to a deeper understanding of the motion of tumbling space debris.

2. Apparatus and methods

2.1 Experimental procedure

To replicate microgravity conditions, a glider flying a sequence of parabolic trajectories was employed. It has been previously demonstrated that a glider can be used to simplify access to earthbound weightlessness. This platform gives access to up to 6 seconds of consecutive microgravity during the parabolic phase of the flight, and an average of 15 parabolas are achieved per flight (see [6] for a detailed discussion). During the microgravity phases of the flight, an object is released in the cockpit by an operator (Fig. 1). The attitude data of the object is recorded using an experimental device described in the next section. An independent accelerometer records the acceleration experienced by the airframe (see methods in [6]). The motion and attitude of the object are also recorded by a monocular camera during the flight.

Figure 1*: Experimental object in microgravity during a parabolic flight in a glider.*

2.2 Data acquisition

The STAG project necessitated the development of an experimental device to capture the motion and attitude of small tumbling objects in a microgravity environment. This device (shown in Fig. 2) can be placed inside small objects. The object used in the first flight campaign was a 3D printed cube, the inertia of which can be varied by adding distributed balancing weights (Fig. 1).

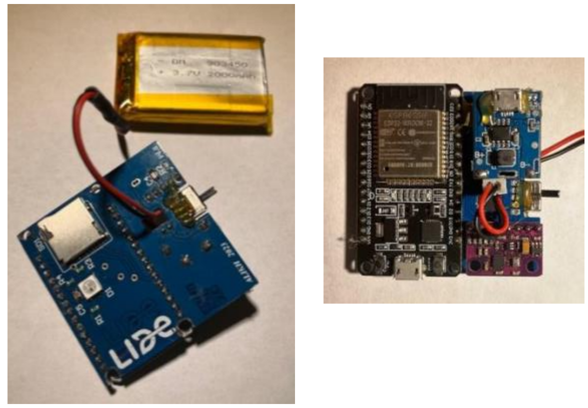

Figure 2*: Data logging device. PCB of the microcontroller and sensors' assembly.*

Table 1: *Device main component list.*

Item	Description	Part number
1	Microcontroller	ESP32 ESP-32S
2	IMU sensor	MPU-9250
3	Pressure and temp. sensor	BMP280
4	Battery	LiPo 1S 2000 mAh

Table 1 lists the main components used in the experimental logging device. An IMU sensor is used to output motion and orientation data, and an extra sensor measures static pressure and temperature. Data acquisition is carried out by the microcontroller which records the raw measurements at a frequency of 15 Hz. The logger system is configured to automatically store the recorded data directly into a text file (ascii format) for ease of post-experiment analysis and data parsing. This file is saved on a standard SD card integrated into the logger (see Table 2 for the content of the text file).

***Table 2**: Content of data files recorded by the logger.*

Column number	Parameter name	Unit
1	timestamp	ms
2	acceleration (x component)	g
3	acceleration (y component)	g
4	acceleration (z component)	g
5	angular rate (x axis)	° / s
6	angular rate (y axis)	° / s
7	angular rate (z axis)	° / s
8	magnetic field (x)	µT
9	magnetic field (y)	µT
10	magnetic field (z)	µT
11	temperature	°C
12	pressure	hPa
13	pressure altitude	m

3. Results

During the initial experimental campaign, two flights were performed, totaling 34 parabolas. Further data from future flights will be added to the open access dataset as they become available.

We present a sample of the data collected during our experimental campaign. Figure 3 shows the altitude of the glider over time for the two initial flights. The glider loses altitude over time and therefore needs to stop the experiment when too close to the ground.

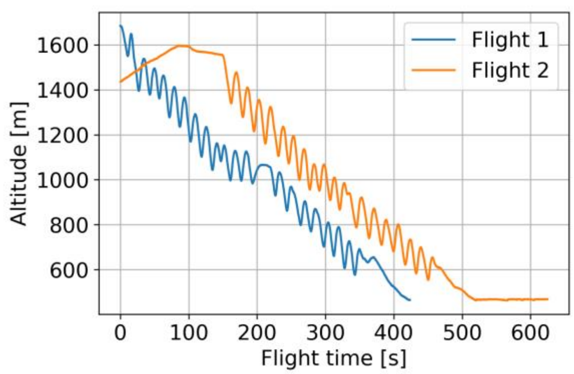

***Figure 3**: Altitude profile of two experimental flights.*

Figure 4 shows the norm of the acceleration vector next to the altitude profile. The figure shows that up to 5.5s of consecutive microgravity (acceleration smaller than 0.1 g) is experienced by the object under test during each parabola, which is in line with previous results [6]. The acceleration experienced by the tumbling object matches the acceleration of the airframe in non-parabolic phases. During the microgravity phases, a few spikes are observed in the object's acceleration. This happens when the object collides with the cockpit walls or is manipulated by the operator, resulting in a change of trajectory.

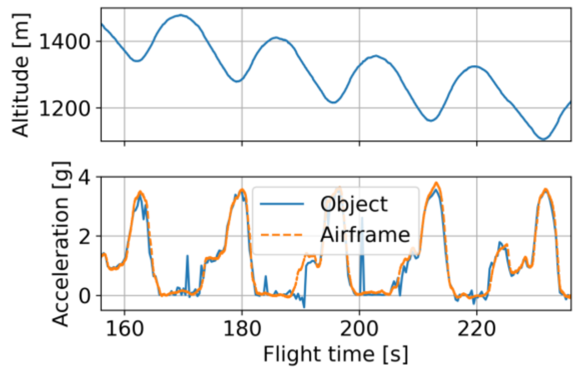

***Figure 4**: Altitude profile (top) and norm of the acceleration vector (bottom).*

Figure 5 shows the angular velocity recorded by the gyroscopic sensor of the IMU in all three axes.

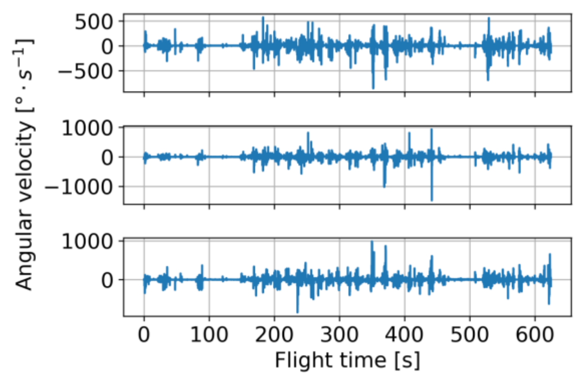

***Figure 5**: Angular velocity in 3 axes.*

Finally, examples of images recorded by the monocular camera at three instants during a single parabola are shown in Fig. 6.

***Figure 6**: Three images captured by the monocular camera during a single parabola.*

4. Discussion

While this paper focuses on data collection and the experimental procedure, and presents the open access dataset, we foresee potential for using the data in various ways:

— Image Processing: Estimation algorithms could be implemented to process the captured images and extract the object's motion and attitude. These results could then be validated with the IMU data.

— Tumbling: Algorithms to propagate in time the short-term response of non-cooperative objects could be tested against the dynamics measured in our experiment.

Some considerations should be taken into account when analysing the data:

— The present experiment is not conducted in vacuum. Residual drag could impact more noticeably the motion of objects with larger surface areas.

— A data assimilation technique should be implemented to process the raw data and provide a reference position and attitude as a more accessible information for users interested in image processing validation.

— A range of small objects with diverse shapes and inertias should be selected to evaluate the effects of internal and external influences on motion. Objects with irregular inertias could demonstrate a more unpredictable tumbling pattern compared to symmetrical objects. This will be the focus of future flights.

5. Conclusions

This paper presents the STAG project, whose aim is to generate an open access dataset on the motion and attitude of tumbling objects in microgravity. The experimental procedure and hardware were described, and sample results were shown. The dataset can be used for validation of attitude estimation techniques based on monocular imagery, and for dynamics analysis and simulation of non-cooperative objects. The dataset will continue to grow as more flights become available, testing different object shapes and inertias.

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Data availability

Links to the dataset, as well as files used for data analysis, are available from the following repository: https://github.com/SpaceLIDE/STAG
The authors also welcome feedback from the users of the dataset to improve future experimental campaigns.

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