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Astrobee Free-Flyer Nozzle Mechanism Summary

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Abstract

This paper details the function, design, and lessons learned during the development of the Astrobee Free-Flyer nozzle. The Astrobee Free-Flyer is a free flying robot used aboard the International Space Station.

Introduction

The Astrobee Free-Flyer is a 12.5-inch cube, battery powered, air propelled free flying robot that navigates autonomously within the ISS (see Figure 1).

Two Astrobee Free-Flyers were launched on NG-11 on April 17 this year. Currently, the “Bumble” Free-Flyer is going through commissioning phase and has successfully completed its first flight. The Free-Flyer “Queen” (Queen Bee) was launched on SPX-18 in July this year.

Propulsion System

Propulsion of the Free-Flyer is provided by two interchangeable propulsion modules (labeled Right and Left in Figure 1) located on the right and left sides of the Astrobee robot. Each module is built around a plenum; the plenum is pressurized by a single centrifugal impeller, which draws in air through a central intake and feeds six exhaust nozzles (see right image in Figure 1). The propulsion system is holonomic in 6-Degrees-Of-Freedom in that it can apply force in any direction and torque about any axis. The propulsion system was proposed during the Personal Satellite Assistant (PSA) project at Ames Research Center in 2003.

Nozzle Design

With a constant impeller speed, the thrust from each of the twelve nozzles has fixed direction and continuously adjustable magnitude, controlled by adjusting the nozzle open area with a servo that actuates gear synchronized flappers. Flight nozzles in the closed and open positions are shown in Figure 2 along with a CAD representation of the gear synchronized flapper drive. The servo motor is an off-the-shelf MKS DS95 servo typically used with hobby RC models allowing for direct control of the thrust level. The nozzle area and impeller are sized to provide the required thrust and air exit velocity performance (Maximum 0.3 N for one nozzle and $\approx 11\mathrm{m/s}$ exit velocity). The forward and aft (X-direction) nozzles are larger to meet operational thrust requirements.

Nozzle Development

Several iterations of nozzles are shown in Figure 3 (left to right nozzles are the earliest to flight designs). The proof of concept nozzle incorporated a single flapper. The geared dual flapper design was developed to minimize thickness and provide better air direction characteristic while providing a high (~0.9) discharge coefficient.

Flapper Slip

Once calibrated, the flapper angular position on the drive elements (consisting of gears and shafts) is fixed and must not slip over the life of Astrobee (5 years). A 10 in-lb slip torque requirement was added in case a flapper jammed and the servo applied full torque (10 in-lb includes a 5X slip factor). Two connections of concern were: 1) the gear press fit to the shafts (drive and flapper shaft), and 2) The integrated flapper clamp to the flapper shaft. The integrated flapper clamp design easily met the slip requirement. This paper will expand upon the final solution of incorporating a straight knurl to increase the slip torque for the press fit gears.

Servo Chatter

During initial testing, some of the hobby grade servos produced a chattering noise when the nozzle held a fixed position (the chatter was magnified by backlash springs that are discussed in the lessons learned section). The chatter was loud and annoying enough to potentially limit operation time. A servo search study was completed (with over 10 different COTS servo models) to find the quietest servo capable of holding the required torque. Additionally, it was determined the chatter could excite the propulsion structure leading to additional noise. This paper will expand upon the testing and solution incorporated to reduce and isolate the servo chatter.

Bearing Installation

Including all the flight and ground unit nozzles, over 800 bearings (6mm and 12mm O.D. bearings) are installed. Two bearing press tools were developed and fabricated that proved reliable for bearing installation and are capable of rework when necessary. This paper will illustrate the tool design and operation that may be useful for other hardware.

Lessons Learned

Limitation of 3D printed plastic

Significant use was made of 3D printed parts during nozzle development (and the Astrobee development in general). ARC Code REM operates two FDM machines capable of printing ABS and Ultem materials. Because early nozzle prototypes were 3D printed, and 3D printed parts were potentially lighter, the initial flight nozzles were designed to be 3D printed. However, when significant issues with outside vendor part quality and reliability issues were discovered during initial assembly, the 3D printed design was quickly dropped in favor of a traditional aluminum machined design. The inlet and grill dividers are the only flight nozzle parts made from 3D printed materials.

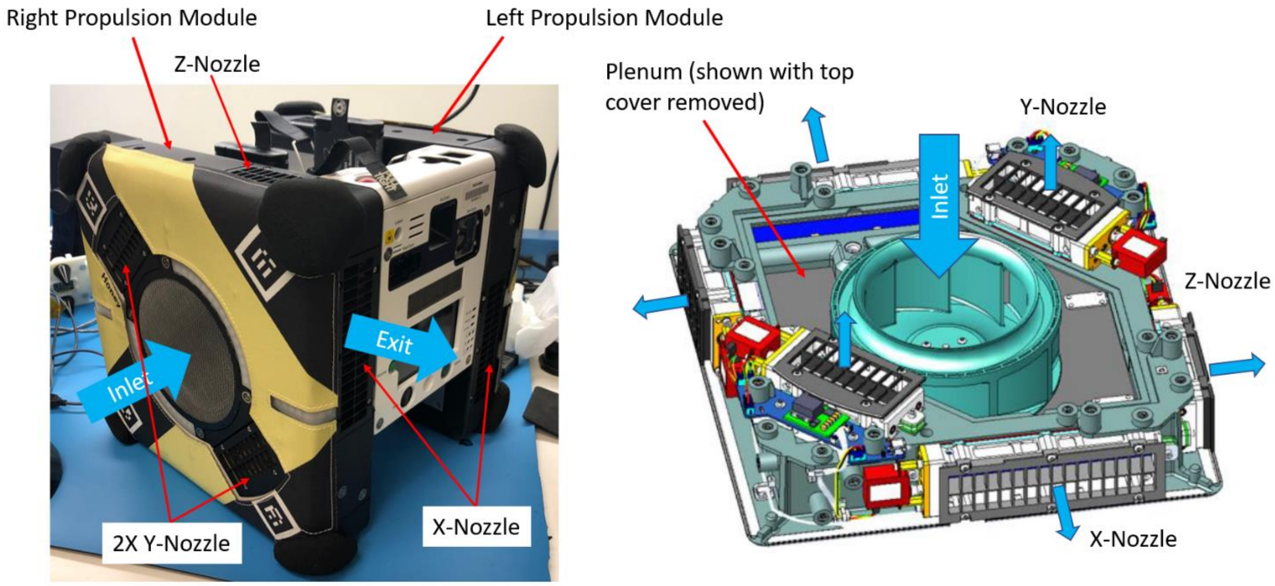
Backlash

The flapper position accuracy is affected by the gear center distance and gear manufacturing quality. Sample gear boxes with different gear center distances were made to decide the center distance and tolerances acceptable for manufacturing and gear mesh feel (no binding). The result was 1.8 degrees of backlash in the flapper angular position (a flapper travels a total of 64 degrees). The 0.04 in-lbf spring to eliminate backlash caused significant servo chatter and eventually started to fatigue and fail during testing. This paper will describe the successful effort to remove the backlash springs and eliminate the unnecessary complexity.

Concluding Remarks

Overall the nozzle design, fabrication and assembly are simple. The author believes the development and processes established during the provide useful insight to other mechanisms.

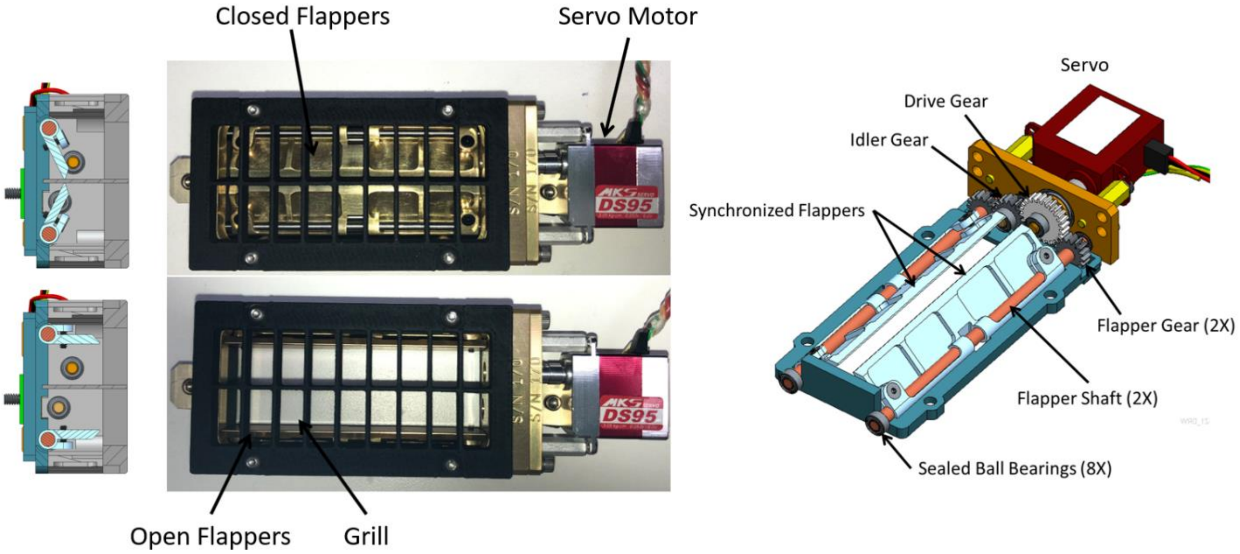
Figures



Free-Flyer

Air flow through an Astrobee propulsion module

Figure 1 – Free Flyer and Propulsion Module



Open and Closed Nozzles

Synchronized Flapper Drive

Figure 2 - Nozzle

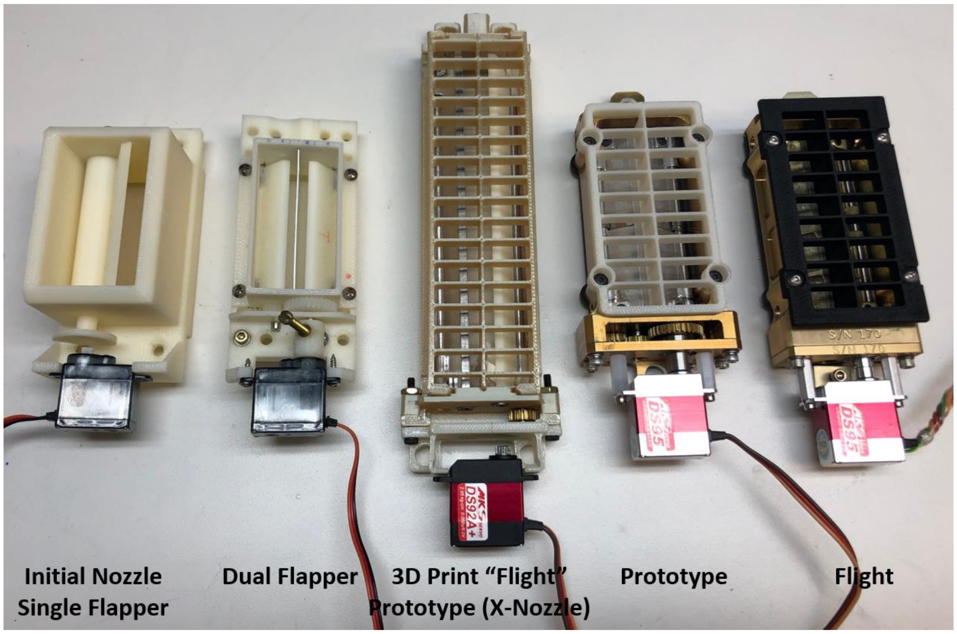


Figure 3 – Nozzle Evolution