Design and development of prototype carpal wrist cold gas propulsion system for attitude control applications

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Abstract. In recent years, the Philippine space program has launched several small-scale satellites, and lately has commissioned its own space program. Research on improving the subsystems of these satellites would be beneficial to future space programs in the Philippines. This paper will detail the process of designing, validating, fabricating, and testing a prototype Carpal Wrist Cold Gas Propulsion System (CW-CGPS). By making use of a carpal wrist’s (CW) hemispherical movement capabilities, the sixteen thrusters could theoretically be replaced by four mounted on opposite ends. Optimization of the propulsion system is based on finding the nozzle design with the most adequate values for thrust, Mach number, and specific impulse while the CW design is validated when it can be calibrated to move as the program dictates. This study uses multiple programs to simulate and verify the design. The conditions of the testing environment are established by resources from international space organizations. Assembly and feasibility are assessed based on the results of the research. It was found that the final optimized system had a model torque of 0.247 N·m, more than enough to overcome the maximum combined influence of the gravity gradient torque of 2.34E-06 N·m and aerodynamic torque of 1.57E-25 N·m. The design, development, and test campaign for the thruster system is presented.

Keywords: Carpal Wrist Manipulator, Cold Gas Propulsion, Nozzle Optimization, Rapid Prototyping, Attitude Control

1. Introduction

Modern artificial satellites are used for gathering large-scale information around Earth. In this regard, miniature designs (CubeSats) have become prevalent due to their cost efficiency [1, 2, 3]. One such microsatellite, Diwata-2, is currently in orbit thanks to the success of its predecessors, proving that research into the development of small satellites is beneficial to the Philippines. Diwata-2 uses magnetic torquers and reaction wheels for attitude and orbit control. These methods are mostly applicable for minute changes in motion but have disadvantages with regards to their dependency on the Earth’s magnetic field. Thrusters or propulsion systems are a more common attitude control and maneuvering method in satellites [2]; this may have more potential in future designs of small satellites in the Philippines. A standard satellite attitude control system (ACS) generally possesses four quad thrusters as a means of attitude and reaction control for a total of sixteen thrusters. Incorporating a robotic component such as the mechanical carpal wrist can decrease this number.

Cold Gas Propulsion (CGP) is a type of propulsion that generates thrust through controlled expulsion of a compressed cold gas. The lack of combustion makes it one of the most economical propulsion systems but also causes it to perform comparatively poor due to simplicity. Improvement of the system
can be done through optimization of its nozzle as the fluid’s exit through the nozzle dictates its performance significantly [4].

The carpal wrist joint is a mechanical actuator that has undergone multiple developments from actuating parallel manipulators. This mechanism was selected to be integrated with the CGPS for its hemispherical pointing capabilities. Its parts were uniquely designed to fit the components of the CGP and integrate other electrical equipment such as stepper motors, sensors, and a microcontroller. Rapid prototyping this mechanism was done by 3D printing the designed parts using polylactic acid (PLA) filament.

The objective of this study is to design and fabricate a model of a working CW-CGPS for attitude control applications. The term “system” in this sense denotes a single CW joint with one thruster attached to its end effector. Its feasibility for attitude control will be based on how well its hemispherical thruster-pointing capabilities satisfy the requirements in an ACS for low earth orbit (LEO) conditions.

2. Nozzle and its Optimization

The nozzle to be used is the convergent-divergent (C-D) nozzle. The four output nozzle parameters that describe the performance and efficiency of a nozzle in a spacecraft are thrust (1), specific impulse (2), exit velocity (3), and change in velocity (4) and can be found using the following formulas [5].

\[
F_e = mV_e + (p_e - p_a)A_e \quad (1)
\]

\[
I_{sp} = \frac{F_e}{mg} \quad (2)
\]

\[
V_e = \frac{4Q}{\pi D^2} \quad (3)
\]

\[
\Delta V = I_{sp} \ln \left( \frac{m_f}{m_e} \right) \quad (4)
\]

C-D nozzles can ideally convert subsonic fluid flow in the converging section to supersonic flow in the diverging section. As the fluid exits the throat section, it swiftly expands which increases the velocity of the fluid as it exits the nozzle. The contour of the bell nozzle promotes fast expansion and more uniform axial flow at the exit compared to the conical nozzle while also preventing shock in the flow. Rao (1958) proposed using parabolic approximation procedures to design near optimum thrust bell nozzle contours [6]. Rao established the independent variables needed in designing a C-D nozzle: throat diameter \((D_t)\), axial length of the nozzle from throat to exit plane \((L_n)\) (or the desired fractional length \(L_f\) based on a 15-degree conical nozzle), expansion ratio \((\varepsilon)\), initial wall angle of the parabola \((\theta_h)\), and nozzle exit wall angle \((\theta_e)\).

3. Attitude Control & Environmental Disturbance Torques

![Figure 1. Theoretical CW Propulsion Application Model.](image)

Figure 1 Shows the application of the thrust vectoring system prototyped in this research. Knowing that a thrust vectoring system is capable of hemi-spherical pointing, the number of thrusters to be used for attitude control is reduced by a fourth providing angular momentum \(H_i\), about the XYZ-axis whose
The equation is given below where \( I_i \) is the moment of inertia about the axis rotation, and \( \Omega_i \) is the angular velocity:

\[
\mathbf{\ddot{r}} = \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} -I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & -I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & -I_{zz} \end{bmatrix} \begin{bmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix}
\]

(5)

The Orbital Velocity is needed in further computations for external forces being experienced by an object at a certain orbit [7]. The equation elaborates on the variables involved below where \( V_o \) is the orbital velocity, \( G \) is the universal gravitational constant, \( m_E \) is the mass of the Earth, and \( r_o \) is the distance of the orbiting object from the center of the Earth:

\[
V_o = \left( \frac{G m_E}{r_o} \right)^{1/2}
\]

(6)

The density behavior in increasing altitudes decreases exponentially and can be estimated using the following equation:

\[
\rho_{atm} = \rho_o \cdot \exp \left( \frac{h - h_o}{H} \right)
\]

(7)

ISO 2533 presents the International Standard Atmosphere Model from 1976 data on the Tropopause layer which had an altitude \( (h_o) \) of 11000 m and a base density \( (\rho_o) \) of 0.3639 kg m\(^{-3}\) [8]. Scale Height is referred to as the change in vertical distance for an atmosphere from its surface to decrease in pressure by 1/e or 0.368. For this case, the earth’s scale height \( (h) \) can be assumed to be 8570 m.

A satellite in space is subjected to Magnetic Torque, Gravity Gradient Torque, Aerodynamic Torque, and torque due to the solar pressure. However, a satellite can only be affected by specific environmental torque/s depending on the altitude of the satellite. In this study the satellite is assumed to be on Region II where the satellite is affected by gravity and aerodynamic forces [9].

With the assumption that the spacecraft is rigid, and the earth is a rigid sphere with a symmetric distribution of mass, the gravity gradient torque can be expressed below where \( T_G \) is the gravity gradient torque about the X principal axis, \( \mu \) is the Earth’s gravitational constant \( (3.986 \times 10^{14} \text{ m}^3 \text{m}^{-2}) \), \( R \) is the distance from the center of the Earth in m, \( \theta \) is the angle between the local vertical and the Z principal axis, \( I_y \) and \( I_z \) are the moments of inertia about Y and Z in kg m\(^2\):

\[
T_G = \frac{3\mu}{2R^2} \left| I_z - I_y \right| \sin(2\theta)
\]

(8)

Aerodynamic torque on a spacecraft is a function of the atmospheric pressure, orbital velocity, projected area in the direction of the orbital velocity, and the spacecraft geometry. Where \( T_A \) is the aerodynamic torque, \( \rho_{air} \) is the density of air, \( A_p \) is the projected area, \( c_{pa} \) is the center of atmospheric pressure, and \( c_m \) is the center of mass of the satellite.

\[
T_A = \frac{1}{2} \rho_{air} C_D A_p V_o^2 \left( c_{pm} - c_m \right)
\]

(9)

4. Programming and Simulation Approaches
Table 1. Initial values of design variables and established constraints.

| Design Variables | Initial  | Lower  | Upper  |
|------------------|----------|--------|--------|
| $R_t$ (mm)       | 0.856637 | 0.5    | 1.5    |
| $R_e$ (mm)       | 2.21371 | 2      | 3      |
| $\theta_n$ (degree) | 61.1773 | 55.05957 | 67.29503 |
| $L_n$ (mm)       | 1.69823 | 1.25   | 3      |
| $\theta_e$ (degree) | 3.063614 | 0      | 5      |

The process of designing and testing an efficient nozzle piece for this project was divided into two phases: Sparse Grid Response Surface Methodology generated through interpolation of the design points for ease of analysis of the performance parameters [10, 11] and Performance Validation through simulation of both the initial and final designs. This involves the use of SolidWorks to generate nozzle profiles and ANSYS FLUENT to create the mesh for the solver. The viscous model used is the k-epsilon turbulence model with the boundary conditions seen in Figure 2 with settings based on environmental conditions in space [12]. After these simulations, the optimization study defined the best combination of values for the four output parameters that would lead to the most effective nozzle with the goal of optimization being finding the global optimum that satisfies the settings as best as possible. The algorithm yielded the three best candidate points which were then verified for further accuracy.

To determine the feasibility of the ACS, environmental and geometric conditions must be established to govern the requirements it must satisfy. A form factor satellite based on the existing Diwata-2 micro satellite serves as the reference point. Its LEO altitude is said to be at 620 km. The values of the torques affecting the said satellite were computed based on the earlier equations and NASA’s dictated conditions for LEO [7] where $G$ is 6.67 E-11 N·m²·kg⁻². Additional constants include Mass of Earth at 5.98 E+24 kg, Earth’s Radius at 6378100 m, orbit radius at 6998100 m, $V_o$ at 7.55 E+3 m·s⁻¹, and $\rho_{atm}$ at 5.00 E-32 kg·m⁻³. All this information can be used to generate a program on MATLAB to examine the behavior of Diwata-2 with the propulsion system in LEO.

5. Design Considerations and Fabrication of Components

The design of the robotic manipulator is based on Dr. Ganino’s development of a parallel actuated singularity free robotic wrist which he calls the carpal wrist [13]. Its main structure is composed of the distal plate (top plane), the arms, and the basal plate (bottom plane).

In this set-up the basal plate is to be fixed to the satellite’s body while the distal plate varies its position corresponding to the desired pointing direction of the nozzle to be attached. Its design is meant to attach the mounts of the stepper motors and fit the basal revolute joints with a shaft.

To avoid arm chain interference and still align with the plate revolute, the shape of the arm halfway curves from 15mm to 7.5mm. This allows hinging freely between 20 deg. and 180 deg. Six identical arms will be produced for the prototype.

The revolute joints are designed to allow chain rotation to its corresponding plate and connect to both the plate and the arm. The outer diameter of the bearing cut is 10mm, making it hold two bearings with a 3mm bore. Aside from having a 15mm x 15mm cross section, the 15mm diameter rounded end is meant to avoid interference when it rotates on its shaft. The extrusions vary because the distal will secure a rotary sensor while the basal connects to the carrier of the planetary gearbox.
6. Results and Discussion

Table 2. Nozzle Parameter Results.

| Output Parameters | Initial     | Percentage Difference (%) | Final     | Percentage Difference (%) |
|-------------------|-------------|---------------------------|-----------|---------------------------|
|                   | Analytical | Simulation                | Analytical| Simulation                |
| Thrust (N)        | 2.56       | 3.72                      | 0.93      | 1.23                      | 7.00                      |
| Specific Impulse (s) | 81.93   | 78.76                      | 87.15     | 86.13                     | 0.29                      |
| Mach Number       | 3.48       | 2.85                      | 4.97      | 4.96                      | 2.44                      |
| Delta V (m/s)     | 1.02       | 0.81                      | 1.09      | 1.01                      | 1.99                      |
| Exit Velocity (m/s) | 630.08  | 585.59                     | 693.16    | 678.45                    | 0.54                      |

Table 3. Nozzle Design Optimization Results.

| Design Variables | Initial | Final | Percentage Difference (%) |
|------------------|---------|-------|---------------------------|
| $\theta_E$ (degrees) | 3.06    | 1.49  | 17.35                     |
| $R_E$ (mm)        | 2.21    | 3.00  | 7.54                      |
| $\theta_N$ (degrees) | 61.18   | 59.90 | 0.53                      |
| $L_o$ (mm)        | 1.70    | 2.81  | 12.36                     |
| $R_t$ (mm)        | 0.86    | 0.50  | 13.14                     |

Following the optimization process for the nozzle, the final design was yielded with the percent difference shown in Table 3. Analytical computations were also done for further validation of the final set of simulations with less than 10% difference between the simulated results. Every performance parameter besides Thrust showed improvement with Specific Impulse increasing by seven seconds implying the final nozzle can generate thrust per unit of propellant. The optimized design can be concluded to have a more efficient performance due to most parameters improving with a negligible decrease in thrust force.

Considering the dimensions of the assumed microsatellite form factor with uniformly distributed mass, forced produced by the cold gas thruster, and the position of the CW end-effector and its angle leads to the following being generated through MATLAB as shown in Figure 4 which shows the relation between the moment of inertia given a specific dimension at a uniformly distributed mass and a surface which shows the relation between angular velocity, mass of body, and amount of time the thrusters is being used. For this example, a cubic body of dimensions based on Diwata-2 with uniformly distributed mass uses two thrusters directed in opposite directions perpendicular to the axis of rotation while given an instantaneous thrust force of 1.2321 N will rotate with angular velocity of 3.01 deg-s$^{-1}$ after 500 ms of firing. Based on the Microsatellite form factor where two thrusters are vectored opposite each other at 90 deg. from its initial position, the torque generated is 0.8247 N-m.
Figure 4. Moment of Inertia and its effect on angular velocity given a specific end-effector position.

Table 4. Disturbance Torques.

| Torque Type | Value |
|-------------|-------|
| $T_G$ (Nm)  | 2.34E-06 |
| $T_A$ (Nm)  | 1.57E-25 |

| Parameter | Value |
|-----------|-------|
| $\mu$ (m$^2$/s$^2$) | 3.99E+14 |
| $R$ (m)   | 6998100 |
| $I_y$ (kg$^2$) | 2.0833 |
| $I_z$ (kg$^2$) | 0.00 |
| $\theta$ (rad) | 0.3491 |
| $\rho$ (kg/m$^3$) | 5.00E-32 |
| $C_D$ | 2.2 |
| $A$ (m$^2$) | 0.25 |
| $\nu$ (m/s) | 7,551.289 |
| $c_{pa} - c_g$ (m) | 0.2 |

Table 4 shows the results for disturbance torques at 620 km altitude for the model satellite. Torque values are expected to increase when increasing the angle of inclination or difference in center of pressure and gravity. Adding the Gravity Gradient and Aerodynamic torques would then yield a maximum disturbance torque of 2.34E-06 N-m which is significantly smaller than the torque generated by the prototype propulsion system which is 0.8247 N-m.

7. Conclusion

The CW prototype was fabricated to match the digital design using rapid prototyping. Upon assembly and calibration, it was proven capable of hemispherical movement and accepting inputs from a computer. A computational fluid dynamics optimization was applied to the nozzle geometry to generate the optimum design as it significantly affects the performance of the whole system. While the decrease in thrust in the final design may be perceived as a loss, the optimized nozzle still performs significantly better than the initial in terms of specific impulse and Mach number which both contribute to thrust efficiency; analytical computations of the initial and final design validate this outcome as well. In terms of the overall feasibility of the system with the two components combined, a form factor satellite was used for comparative analysis on the adequacy of the working system with the computed requirements for an ACS in LEO conditions. The designed system more than compensates for the disturbance torques in the given conditions even for higher displacements of angle $\theta$ and difference of centers. It can therefore provide the appropriate thrust for orbit maintenance for the model satellite used. Because the values generated through simulations cannot be matched by the prototype, the propulsion setup needs further work and new parts in order to become capable of accepting data to serve as an ACS. The final optimized nozzle still performs significantly better than the initial nozzle in terms of thrust and exit velocity which both contribute to thrust efficiency. The researchers have successfully designed and fabricated a working CW-CGPS given the resources available and hope this can be integrated in future micro satellite missions.

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