DESIGN AND DEVELOPMENT OF A TEST SETUP FOR REACTION WHEEL SYSTEMS OF NANOSATELLITES

Muhammed Hayri KOC[1,+], Umut UNLU[1], Tarık KUVAT[1], Cenk ULU[1]
[1]Department of Mechatronics Engineering, Yildiz Technical University, Besiktas Istanbul Turkey
m.hayri.koc@gmail.com, unlu0413@gmail.com, tark9703@gmail.com, cenkulu@yildiz.edu.tr

Abstract

Nanosatellites have gained an important place in space applications thanks to developing technology. For a successful operation, attitude determination and control systems in satellites are vital. A reaction wheel system is the widely used drive system for nanosatellites. An electric motor driven reaction wheel is a system that operates utilizing from conservation of momentum and law of action and reaction. In this study, the design and development of a test setup for reaction wheel systems of nanosatellites are given. By using this test setup, different configurations of reaction wheels can be tested, performances of different control methods can be evaluated, and the energy efficiency of the whole system can be determined. Additionally, measured test data such as orientation angles and system current, voltage, and power can be recorded and monitored via the developed user interface. The test setup consists of a platform, reaction wheels, and a control unit. The mechanical design of the test setup which allows changing reaction wheel configurations is developed in Solidworks software. Modeling and control studies are performed in Matlab Simulink environment for brushless dc motor driven reaction wheels. The electronic control unit is designed, and Raspberry Pi is used as a controller. The test platform is produced by using 3d printer and then, subcomponents (electrical control equipment) are assembled into the platform. The functionality and performance tests of the system are performed successfully. The PD control performance results for attitude control of the satellite with the specific reaction wheel configuration are given. These results match the simulation results and validate the system design.

Keywords: Reaction Wheel, Satellite, Attitude Control, Orientation, PD controller

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NANO UYDULARIN TEPKİ TEKERİ SİSTEMLERİ İÇİN TEST DÜZENEĞİ TASARIMI VE GELİŞTİRİLMESİ

Özet

Nano uydular gelişen teknoloji sayesinde uzay uygulamalarında önemli bir yer edinmiştir. Başarılı bir operasyon için uydularda yönelim belirlenmesi ve kontrol sistemleri hayati önem taşımaktadır. Tepki teker sistemleri nano uydular için yaygın olarak kullanılan bir yönelim tahrik sistemidir. Elektrik motoru tahrikli bir tepki tekeri, momentumun korunumu ve etki-tepki yasasından yararlanarak çalışan bir sistemdir. Bu çalışmada, nano uydularda tepki teker sistemleri için bir test düzeneğinin tasarımı ve geliştirilmesi verilmiştir. Bu test düzeneği kullanılarak tepki tekerlerinin farklı konfigürasyonları test edilebilmekte, farklı kontrol yöntemlerinin performansları değerlendirilebilmekte ve tüm sistemin enerji verimliliği belirlenebilmektedir. Ek olarak, oryantasyon açıları, sistem akımı, voltajı ve gücü gibi ölçülen test verileri, geliştirilen kullanıcı arayüzü aracılığıyla kaydedilebilmekte ve izlenebilmektedir. Test düzeneği, bir platform, tepki tekerleri ve bir kontrol ünitesinden oluşmaktadır. Tepki teker konfigürasyonlarının değiştirilmesine izin veren test düzeneğinin mekanik tasarımı Solidworks yazılımında geliştirilmiştir. Matlab Simulink ortamında fırçasız dc motor tahrikli tepki tekerleri için modelleme ve kontrol çalışmaları yapılmıştır. Elektronik kontrol ünitesi tasarlanmış ve Raspberry Pi kontrolör olarak kullanılmıştır. Test platformu 3d yazıcı kullanılarak üretilmiş ve ardından alt bileşenler (elektrik kontrol ekipmanları) platforma monte edilmiştir. Sistemin fonksiyonel ve performans testleri başarıyla gerçekleştirilmiştir. Spesifik olarak seçilen bir tepki teker konfigürasyonu ile uydunun tutum kontrolü için PD kontrol performans sonuçları verilmiştir. Bu sonuçlar simülasyon sonuçlarıyla eşleşmekte ve sistem tasarımını doğrulamaktadır.

Anahtar Kelimeler*:* Tepki Tekeri, Uydu, Tutum Kontrol, Yönelim, PD Kontrolcü

1. Introduction

Satellites have vital importance among space applications from communication to the defense industry. The importance of traditional small satellites has been recognized and reaffirmed by the science community, particularly in Astrophysics, Heliophysics, and Earth Sciences [1]. Currently, satellite design is trending toward nanosatellites primarily because of their lower cost and ease of launch. It is a necessity to determine its attitude and control its orientation while a satellite having an operation. Because of the relatively small moment of inertia and available power of nanosatellites, their attitude control is particularly difficult [2].

The drive system commonly used in nanosatellites is the reaction wheel system. Reaction wheels are electric motor driven mechanisms that used to control the orientation of satellites for specific purposes such as focusing the target [3,4]. Researches on reaction wheels generally focus on energy minimization, control methods, and wheel configurations.

Since the reaction wheel systems are electric motor driven systems, energy consumption should be minimized for the use of multiple reaction wheels [5]. In [6], the effect of triple and quadruple reaction wheel alignments on the energy efficiency of the system is investigated. In [7], a design method for optimal configurations of reaction wheels considering re-configurability is proposed. In [8], the determination of the optimum angle for the tetrahedral pyramidal alignment of the reaction wheels to minimize energy consumption is given. In [9], a reconfigurable control system is designed based on the error quaternion model to recover control in abnormal conditions. In [10], the current control and speed feedback compensation control methods are compared for satellite attitude control. In [11], reaction wheel design for Cube-Sats satellite by considering the limitation of size and mass is presented. However, as a result of these studies, a test setup has not been revealed.

In [12], a test setup is developed for reaction wheels to observe possible system errors and to design a controller for the 4-wheel pyramidal tetrahedral configuration. However, this test setup is valid only for the class of satellites having the pyramidal configuration with 4-wheel. In [13], the ease of use of brushless DC motors and the correlation between the moment of inertia of the wheel and the energy efficiency is investigated. In [14], a low cost yaw controller system is developed for a CubeSat prototype, which tracks a remote setpoint signal. Since this experimental study only focuses on yaw control, it cannot address the whole dynamics of the reaction wheel system of a satellite. In [15], the design and development of 3-axis reaction wheel for

STUDSAT-2 is given. This study focuses on tetrahedral configuration and motor selection for a reaction wheel system. It also aims to minimize the mass of flywheels. In [16], the performance of Low Earth Orbit microsatellite attitude control systems using tetrahedral configuration is evaluated. In this study, tetrahedral configuration and classical three wheel configurations are presented. However, at the end of these studies, a test platform that makes it possible to apply different control methods and test the effects of different configurations of reaction wheels on satellite dynamics and energy consumption is not presented.

In this study, the design of a new test setup for reaction wheel drive systems of nanosatellites is presented. This test setup allows us to change the configuration of the reaction wheels. Thus, this setup makes it possible to observe the effect of the different configurations of the reaction wheels physically and numerically on the orientation dynamics of the satellites. By using this test setup, the effect of wheel configurations on energy consumption and the dynamic performances of the satellites can be tested at the design phase. Additionally, the attitude control performance of the designed nanosatellites can be evaluated for different control strategies via the user interface.

2. Design of Reaction Wheel Test Setup

2.1. Design Requirements

The design requirements determined as a result of the research on the reaction wheels for nanosatellites are shown in Table 1.

Table 1. Design Specifications

Max. Mass	2 kg
Max. Torque	2 mNm
Size	20 x 20 x 20 cm
Min. Operation Time	20 min
Input Voltage	12 V
Communication	Wireless
Functions	Configurable wheel array
	Suitable for 3 and 4 wheels
	Applicability of different control methods

2.2. System Architecture

Depending on the design requirements, the general system architecture of the test setup is determined as shown in Figure 1.

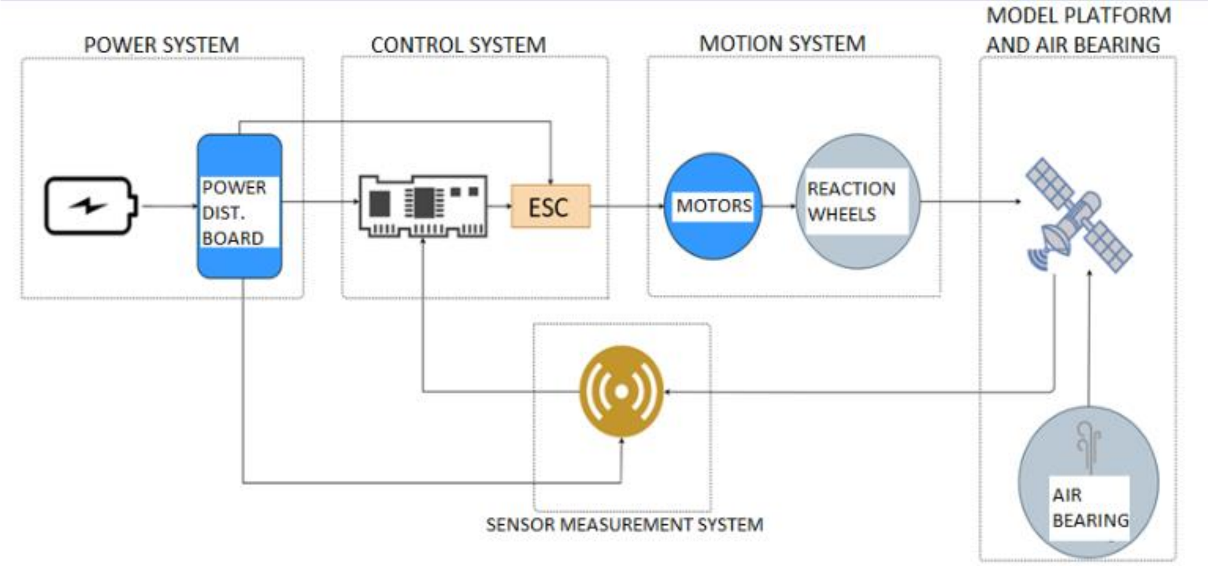

Figure 1. General system architecture

The system contains subsystems. These are a power system including a battery and power distribution board, a control system including Raspberry Pi and electronic speed controllers, a motion system including brushless DC motors and reaction wheels, a sensor system including an inertial measurement unit and voltage-current sensors, and a model satellite platform including an air bearing to reduce friction effect.

2.3. Mechanical Design

In this study reaction wheels, the model satellite platform, and the airbed are designed on Solidworks environment. Depending on calculations for torque balance between the wheel and satellite platform, the required dimensions of the reaction wheel are determined. The design of reaction wheels is shown in Figure 2.

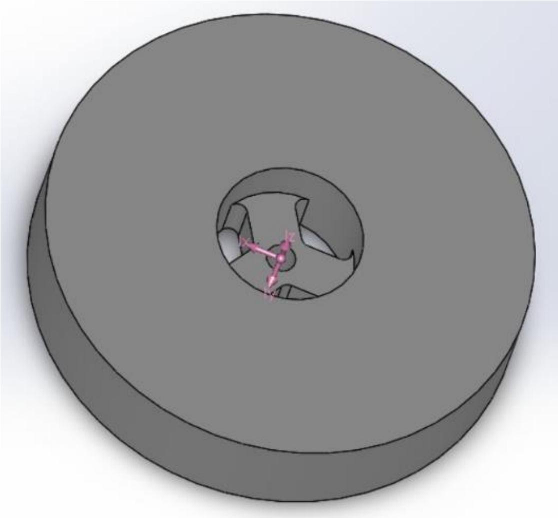

Figure 2. Reaction wheel design

The model satellite platform is designed as a reconfigurable structure in order to allow different reaction wheel configurations. In this way, different reaction wheel configurations can be realized and evaluated on the test setup by considering different requirements. The model platform providing the specified requirements for the 3-wheel configuration is shown in Figure 3. Similarly, the configured model platform for the 4-wheel configuration is shown in Figure 4.

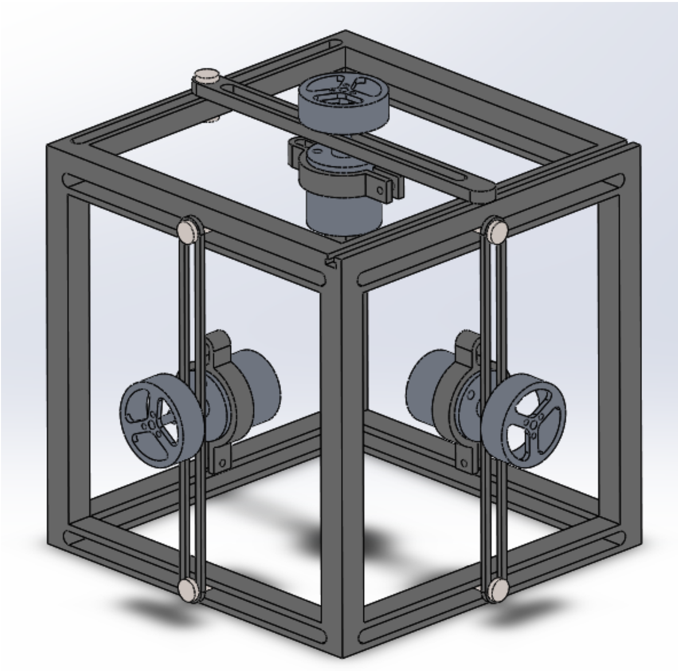

Figure 3. 3-wheel configuration

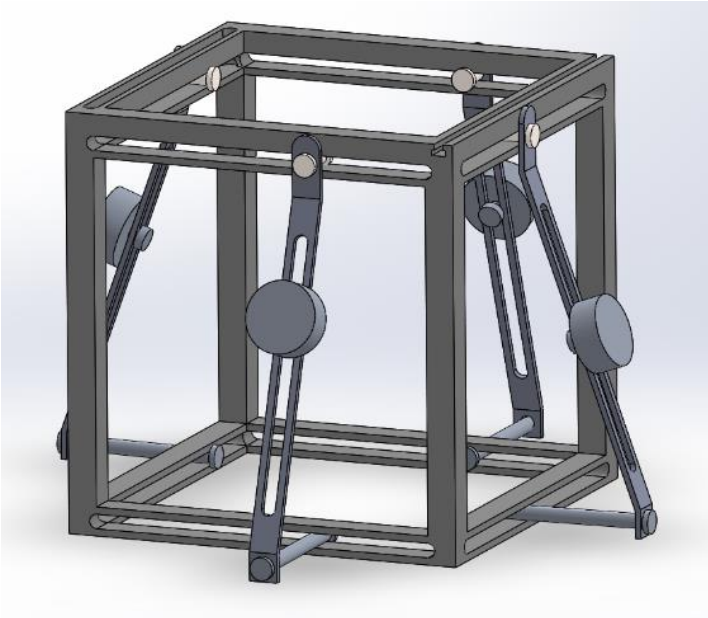

Figure 4. 4-wheel configuration

Many testing methods exist which simulate weightlessness; however, these methods are often not as effective as using an air bearing because of additional forces that arise from friction and countering gravity [17]. The purpose of the air bearing is to allow rotation about all three axes without producing significant external forces. The air bearing of the system is designed on Solidworks environment by considering the pre-determined requirement. The air bearing design is shown in Figure 5.

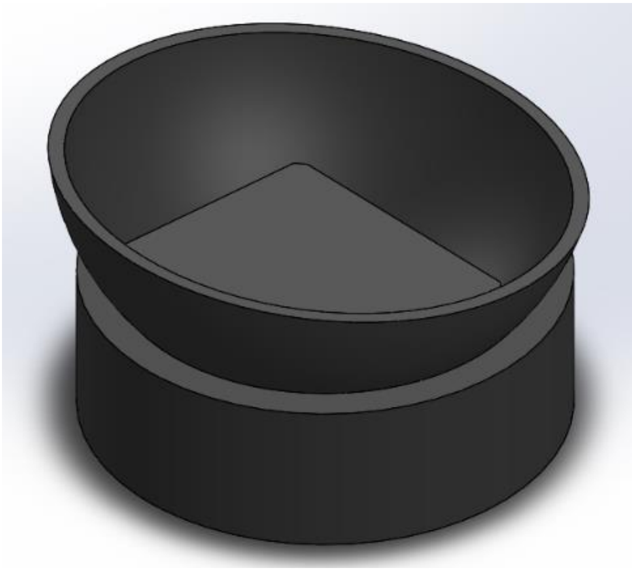

Figure 5. Air bearing design

2.4. Electrical Design

The electrical system of the test setup consists of 12V LiPo battery, power distribution board, Raspberry Pi 3 B+ as a controller, electronic speed controllers, brushless DC motors, and sensors. The electrical design of the system is shown in Figure 6.

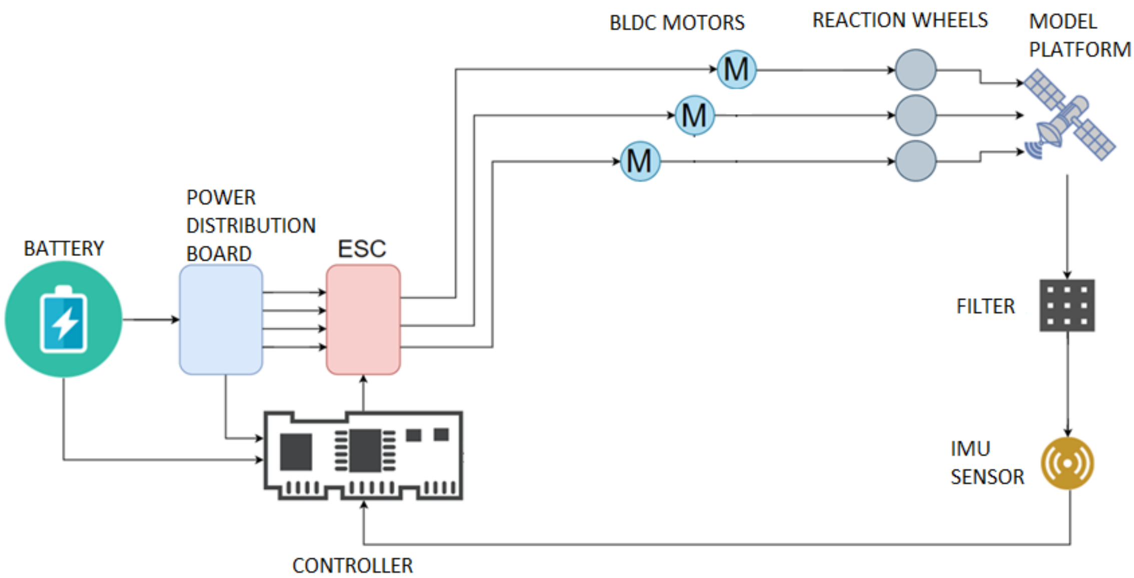

Figure 6. Electrical design

Depending on system design specifications, ProFuse 3S LiPo 1350 mAh battery is chosen as the power supply of the system to meet the ability to run the system for 20 minutes. To provide suitable 5V & 12V power distribution, Matek PDB-XT60 W/BEC with 5V and 12V outputs and 4 ESC connections is used. Raspberry Pi 3 B + is chosen as the controller because of its I/O pin number, 1.2 GHz processing speed, and wireless communication feature via Wi-Fi module.

Depending on the torque and speed requirements, Portescap 22ECT35 Ultra EC is determined as the motors to be used in the system. For the control of these motors, FVT Little Bee 20A, which can provide double direction speed control with BlHeli Suite software, is chosen as a brushless motor driver. Additionally, MPU6050 sensor is used for position feedback. For the measurement of the voltage and current values of the system, Max471 current and voltage sensors are used in the design.

The electrical system is simulated in MATLAB environment by modeling the whole satellite system. The system Simulink model is shown in Figure 7, and the system response is shown in Figure 8.

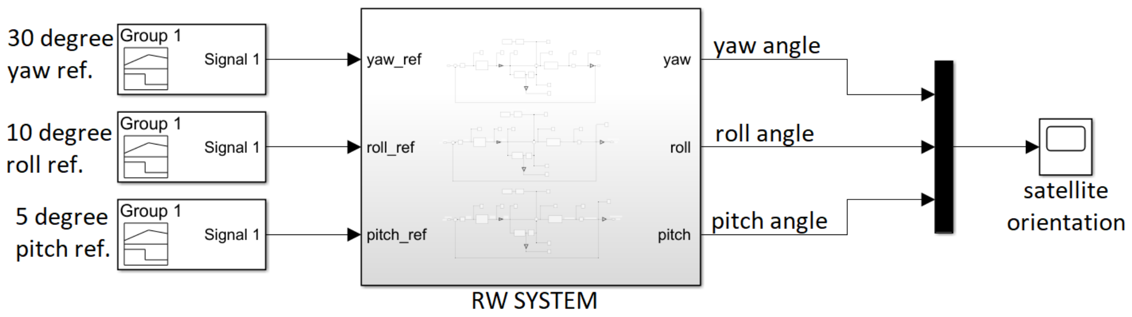

Figure 7. Simulink model

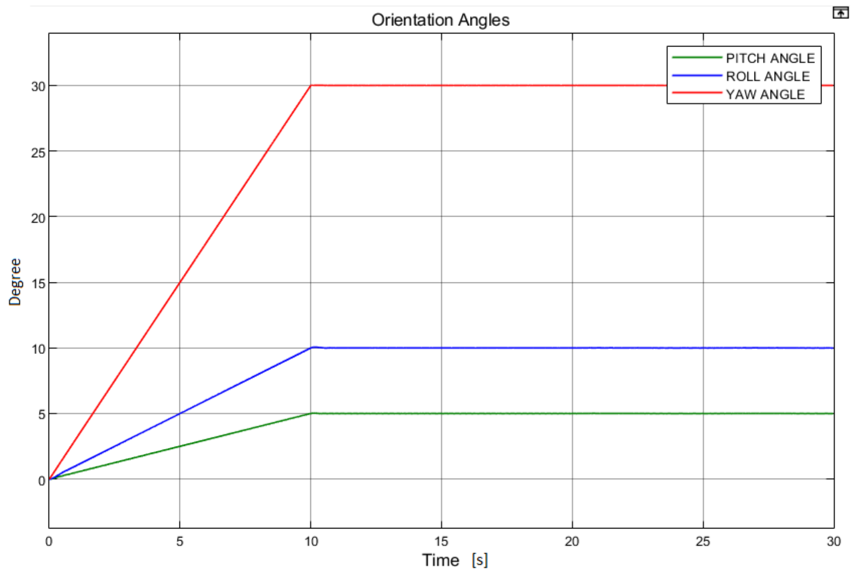

Figure 8. Model response

2.5. User Interface Design

The user interface is developed in Python environment. Instant orientation angles of the system can be monitored with this developed interface. Through this interface, the reference yaw, roll, pitch values, and PID parameter values can be entered. The instantaneous orientation and power consumption of the system are monitored on the interface during the operation. The designed user interface is shown in Figure 9.

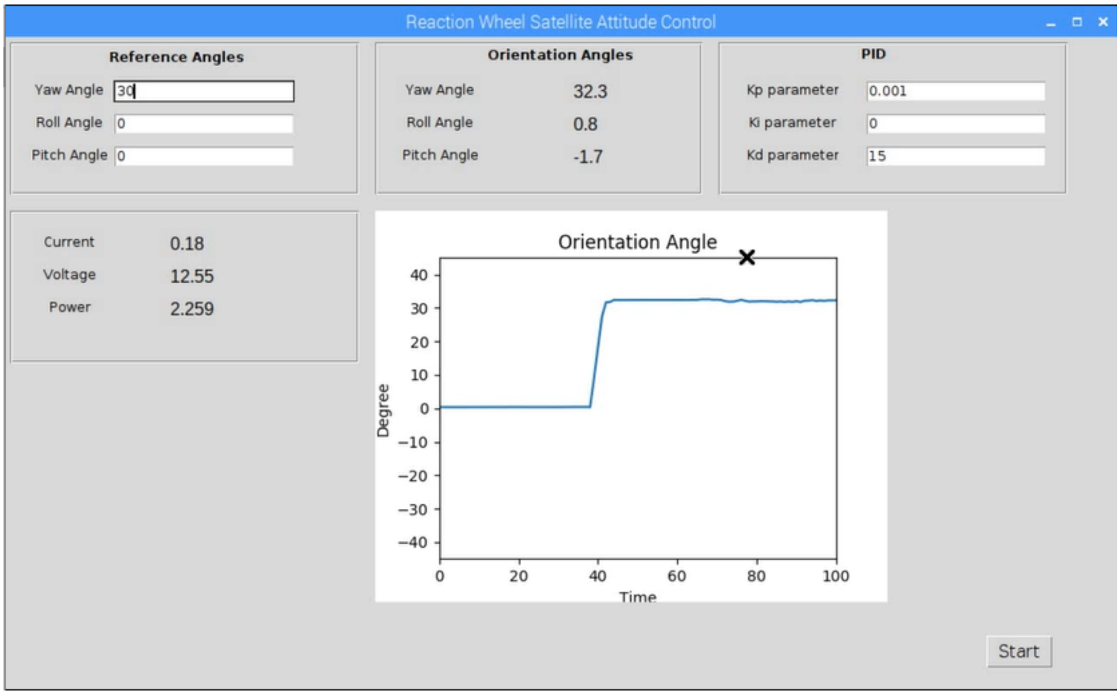

Figure 9. User interface

3. System Integration and Tests

The final design of the entire system containing the model satellite platform, reaction wheels, electronic equipment, and air bearing is shown in Fig. 10.

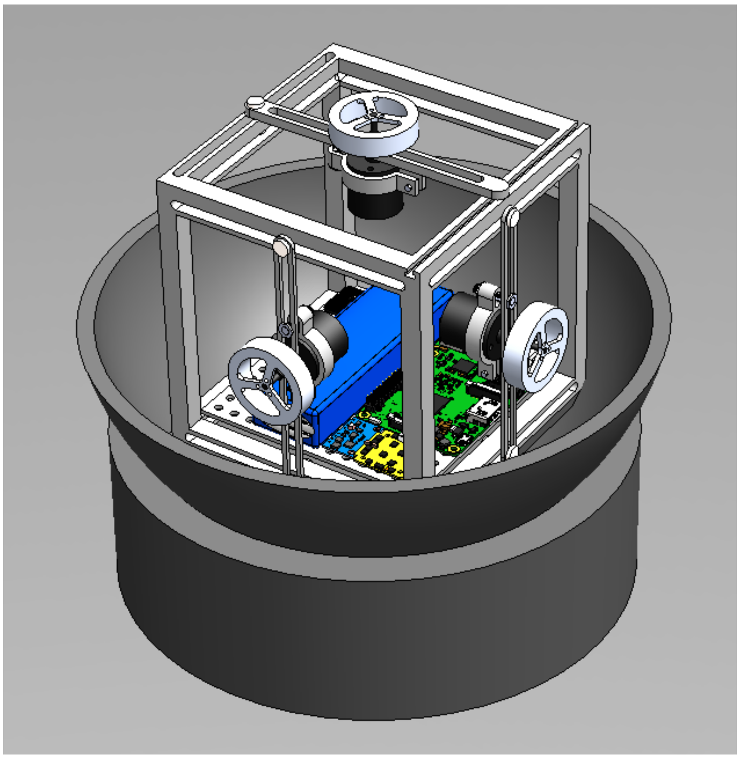

Figure 10. The system final design

The designed platform is produced and its system integration is concluded. The integration of the model platform, electrical system, and reaction wheel drive system is shown in Figure 11. The developed entire system including air bearing is shown in Figure 12.

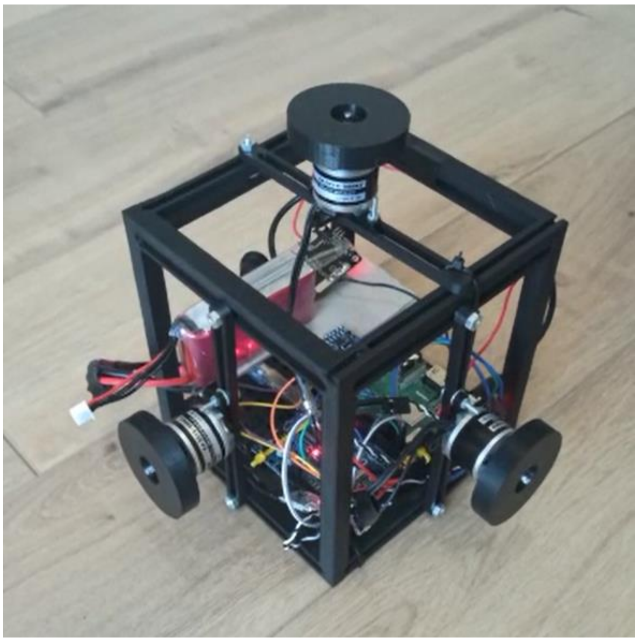

Figure 11. Integration of the system without air bearing

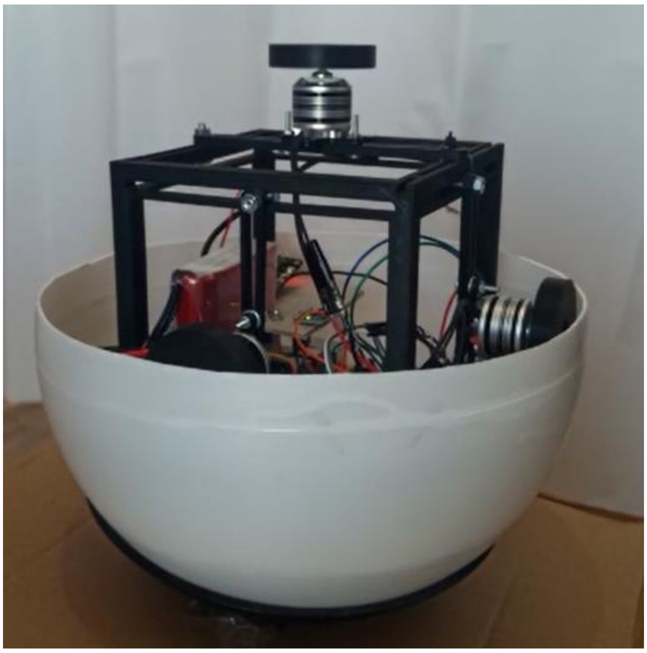

Figure 12. Entire system integration

Basic functional tests are carried out on the system using two different PD controllers. As a result of these tests, the energy consumption values of the system are obtained as shown in Table 2.

Table 2. Test Results

Test No	Reference Orientation Angle	Kp	Kd	Settling Time	Power Consumption
1.	30-degree yaw	0.001	15	3.49 s	51.89 W
2.	30-degree yaw	0.005	20	2.87 s	45.56 W

Figure 13 and Figure 14 show the obtained orientation angle graphics for test-1 and test-2, respectively.

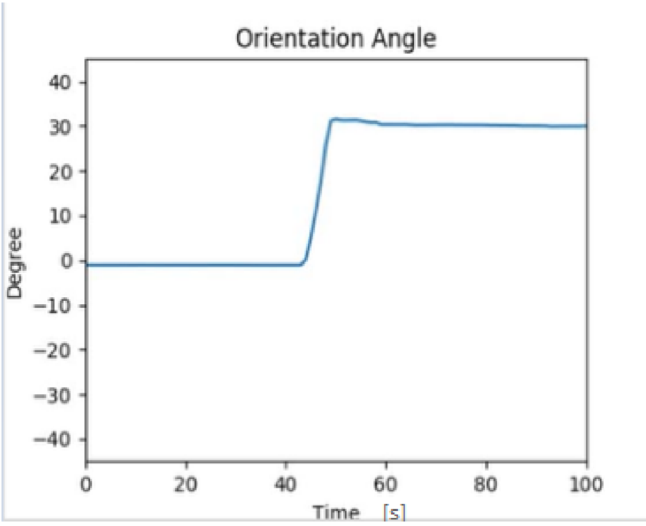

Figure 13. Orientation result for test-1

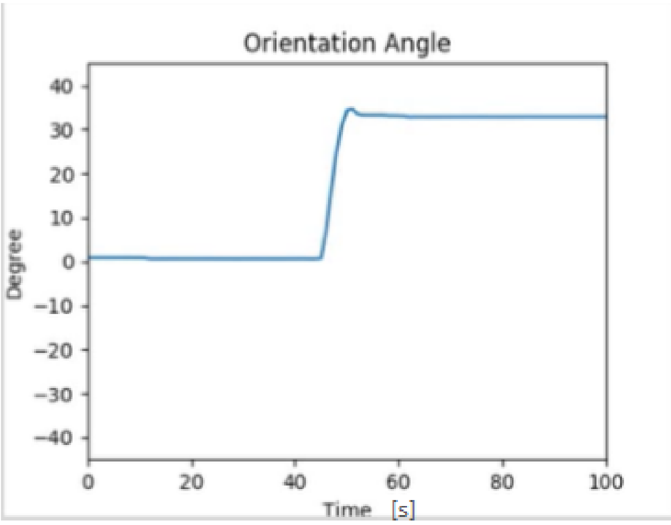

Figure 14. Orientation result for test-2

As it is seen from Figure 13, Figure 14, and also Table 2, by using the developed test setup, the controller performance of the reaction wheel system and its energy consumption can easily be obtained. Additionally, by using this test setup, different control strategies can be applied and related controller parameters can be adjusted effectively.

4. Conclusion

In this study, an experimental setup is developed for the design and testing processes of reaction wheel drive systems of nanosatellites. With this experimental setup, drive systems with different reaction wheel configurations can be evaluated by changing the reaction wheel alignments. Via the user interface, PID controller parameters can be set and instantaneous orientation and power consumption values can be monitored. Additionally, the orientation of the model platform can be monitored graphically. Using the developed test setup, the design of the attitude control system of nanosatellites can be carried out more effectively.

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