Modeling, control and navigation of aerospace systems

Theses of the Ph.D. Dissertation

Al hemeary Nawar

Thesis Advisors:

Dr. Gábor Szederkényi, DSc
Dr. György Cserey, PhD

Pázmány Péter Catholic University
Faculty of Information Technology and Bionics
Roska Tamás Doctoral School of Sciences and Technology

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1 Aim and motivation

The first research objective of this work was the model-based thermal analysis and control of a small satellite (CubeSat) to study the possibility and conditions of the fuel tank installation. Next, an optimization-based approach considering control inputs was exploited to investigate an optimal solar panel ratio to upgrade a CubeSat power system. Finally, GNSS data prediction and synchronization investigations were conducted between the INS sensors and the GNSS receiver in order to enhance the navigation data. The motivation for the research is briefly summarized as follows:

CubeSat functionality. The CubeSat Project was started in 1999 as a collaborative effort of California Polytechnic State University and Stanford University to develop standards for small satellites. Initially, a CubeSat was defined as a ten-centimeter cube weighing one kilogram or one unit (1U). All satellites, including CubeSats, comprise elementary survivability and mission progress subsystems (buses) [1; 2]. Propulsion subsystem (bus) engineering is becoming more critical as the number of CubeSats grows. Innovative propulsion systems are needed to provide rotational attitude control. A thermal control bus is essential to avoid the CubeSat freezing or overheating due to the extreme thermal conditions in space. This system is accountable for securing optimal thermal conditions for satellite components to operate efficiently [3; 4]. Moreover, a CubeSat power bus, which includes solar panels and batteries, is constrained by the small surface area. Thus, computing optimal photovoltaic panel areas is essential [5].

Navigation systems. A global navigation satellite system (GNSS) is used throughout all stages of flight and activates high-accuracy landing performance. Besides accuracy, navigation systems must provide high integrity, continuity, and availability levels [6; 7]. An inertial navigation system (INS) estimates the airborne location, velocity, and attitude, incorporating inertial components' measurement data and initial system parameters. However, even ideal inertial components produce results with errors because of several interferences, which significantly affect the accuracy of INS [8]. Furthermore, the GNSS requires a direct line of sight between the satellite and the receiver, and it may suffer a few seconds of blocking for different reasons. The INS inaccuracy increases with time squared over time due to double integration. Therefore, both techniques are usually integrated to achieve a high-performance navigation system [9].

2 Methods of study

The follow-up on these research fields is to create mathematical models to interpret the key issues that need investigations based on physical laws and potentially simplifying assumptions. First, a thermal mathematical model has been derived describing a CubeSat surface and central propellant tank thermal behavior along with its orbital motions. Next, this model was employed to investigate the satellite's thermal behavior and the thermal transition responses with a feasible passive control synthesis to regulate CubeSat specific element temperatures fulfilling power limitations in the CubeSat throughout its orbit. Then, the active thermal was selected to regulate tank temperatures at the reference temperature value and eliminate the CubeSat propellant thermal fluctuations along the satellite orbit. Finally, because power is the most concerning subject in a CubeSat, an optimization-based model-predictive approach was developed to simultaneously design an optimal solar panel ratio considering the feasible heating power delivered to the system and the propellant tank thermal responses throughout the CubeSat orbital motion.

To deal with navigation accuracy problems, a KNN predictor algorithm is proposed at the GNSS receiver's output to predict between samples of instant GNSS data for synchronization purposes with INS. Also, an ultra-tightly coupled integration technique has been exploited to correct inertial navigation system (INS) measured data with accumulated errors over time, based on GNSS received data. A simulation framework in MATLAB has been developed to study four different integration scenarios containing data-blocking consequences of different lengths using real data measurements. The obtained results have shown that the computed signals of the GNSS/INS integration yield more accurate position data when the GNSS signal is blocked. However, the proposed integration technique is able to maintain sufficiently precise localization even when GNSS signals are not available for 1, 4, or 8 seconds. The physical background of the applied KNN algorithm guarantees this advantageous feature.

3 Summary of the results

- The simulation results showed that the CubeSat surface and propellant temperatures were higher than their respective temperature limits for the case in which the CubeSat surface was made of an uncoated aluminum alloy, as shown in Figure 1. Therefore, I assumed a polished CubeSat surface with magnesium oxide-aluminum oxide paint. The simulation results then showed that the CubeSat temperatures were reduced, as illustrated in Figure 2.
- The fuel tank regulated temperatures (*employing a classic PID controller*) have been examined for two orbits, as shown in Figure 3. In order to improve the thermal response, an anti-windup technique was applied, as shown in Figure 4.
- A linearization-based thermal regulation synthesis for the CubeSat fuel tank was derived. The simulation results in Figure 5 presented the linearization-based technique's capability to control the fuel tank temperature at (*290 K*) with an appropriate thermal response.
- An MPC framework is exploited to integrate active and passive control strategies for an appropriate control input signal ($\dot{Q}_c$) and an optimal solar panel area ($\lambda\ A$), which covered three faces of the CubeSat surface. The simulations indicated that the optimal solar panel ratio changes depending on the tolerances of the acceptable reference temperature value and the amount of rabbling in the thermal response. For instance, when the fuel tank reference temperature value was set to 300 K and the thermal fluctuation of the satellite fuel tank temperatures in orbit was set to ± 3 K, the optimal ratio of the solar panel was $\lambda = 0.7123$, as illustrated in Figure 6.
- A KNN predictor is used to predict between sampling instant of the GNSS receiver for synchronization purposes between the two systems (INS and GNSS), as shown in Figure 7. An ultra-tightly coupled GNSS/INS integration system is designed and implemented to achieve integration between the INS and GNSS techniques. Figure 8 presents the 3-axes simulations of the GNSS/INS integrated positioning, INS, and GNSS signals, incorporating 8 seconds of a lost signal from GNSS.

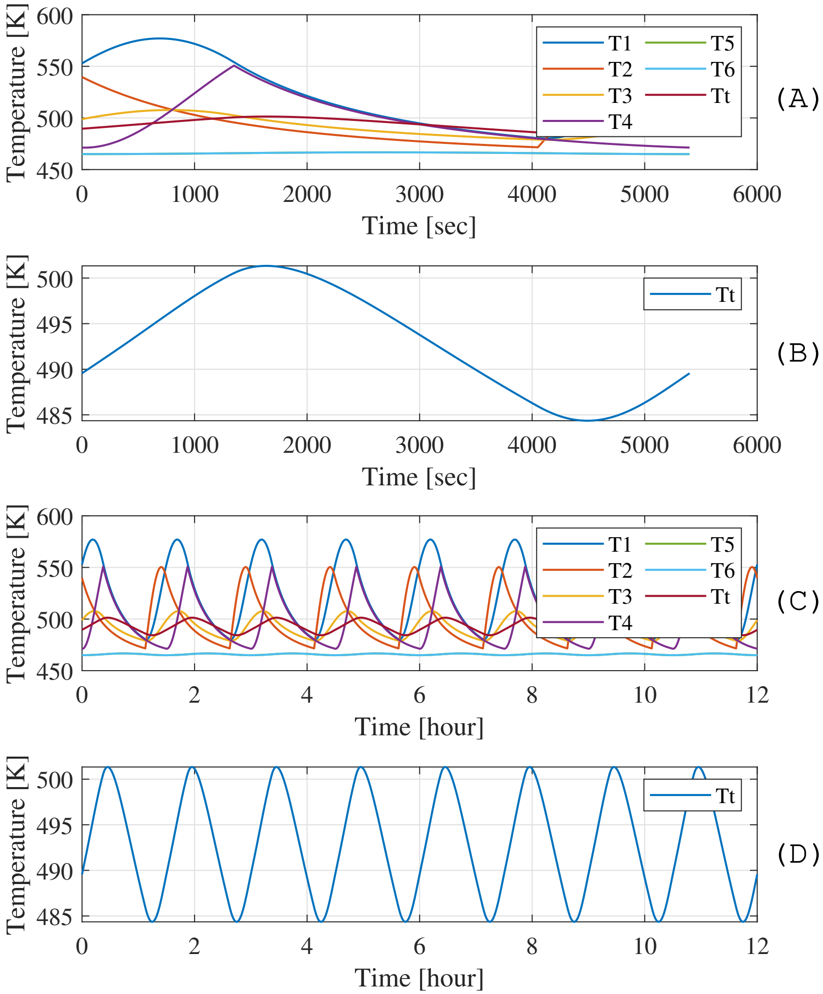

Figure 1: Simulation the CubeSat heat rates assuming aluminum-uncoated surface over orbital motion

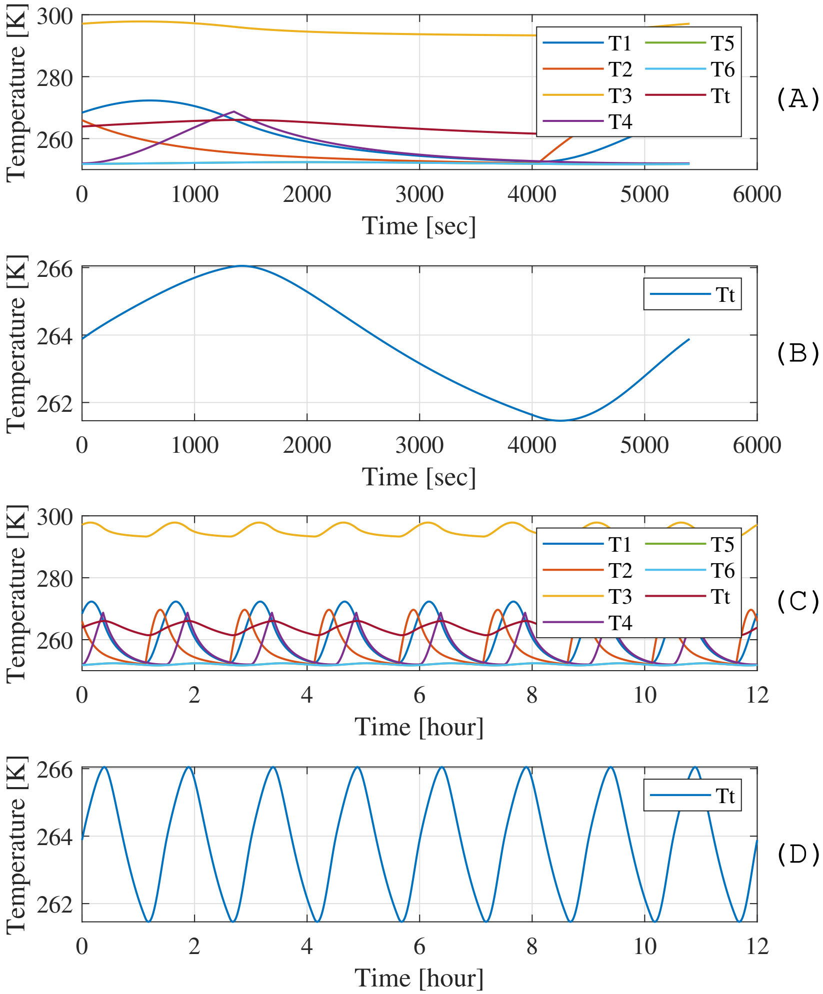

Figure 2: Simulation the CubeSat heat rates assuming aluminum-coated surface over orbital motion

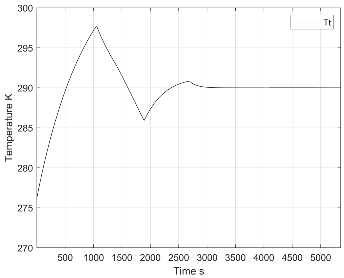

Figure 3: The regulated fuel tank temperature by using a simple PID controller

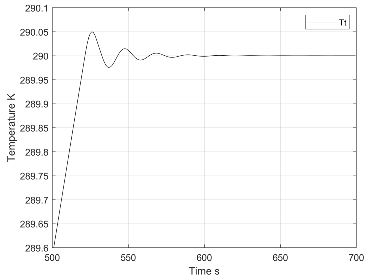

Figure 4: The regulated fuel tank temperature by using an anti-windup PID

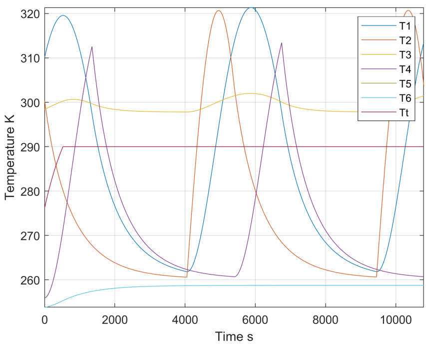

Figure 5: CubeSat surface and its fuel tank thermal behaviors via linearization-based controller and heating power limited at 1.5 W

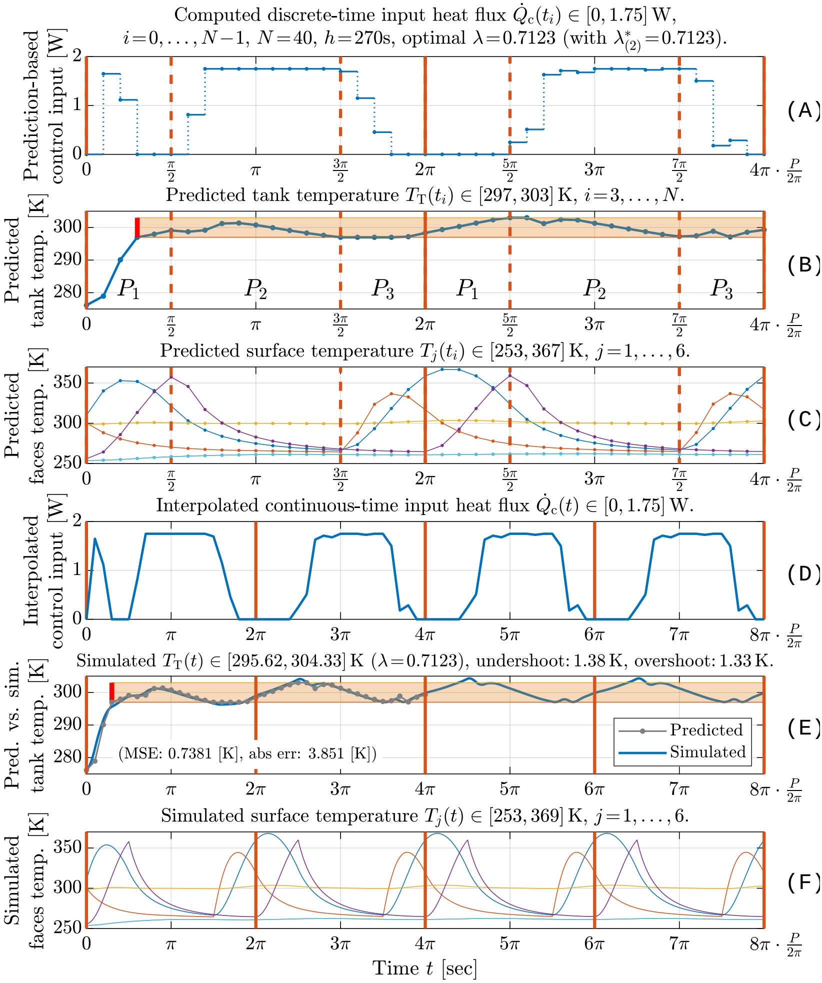

Figure 6: High power ($\dot{Q}_c \leq 1.75$ W) MPC design enforcing a higher baseline tank temperature (T_t = 300 K) but allowing higher (±3 K) fluctuation

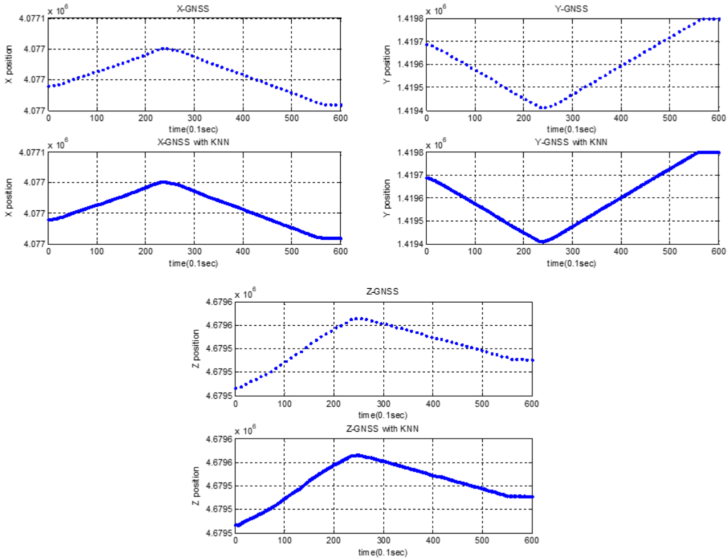

Figure 7: The drone trajectory coordinates in (X, Y, and Z) when using the GNSS data without predictor and GNSS data with the KNN predictor

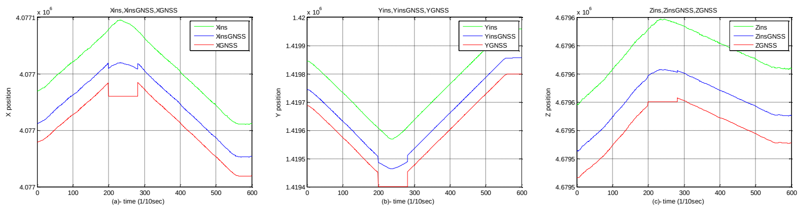

Figure 8: The positions in three coordinates (X, Y, and Z) for INS, GNSS, and integration of GNSS/INS with signal blocking of (8 s), respectively

4 New scientific contributions and thesis points

The main scientific contributions of the dissertation are summarized in the following theses.

Thesis 1 *Nonlinear thermal modeling of a CubeSat* **(Chapter 2)**

I have developed a lumped dynamical model describing the surface and internal propellant tank temperatures of a CubeSat performing orbital motion. First, the thermal model in the nonlinear input-affine form, containing seven differential equations for three time intervals and a time-varying disturbance due to orbital motion, has been derived using physical laws and simplifying assumptions. Moreover, I have given the control-oriented Quasi-Linear Parameter Varying (quasi-LPV) form of the model.

- The simulations showed that the temperatures on the CubeSat surface and fuel tank can be efficiently decreased by appropriately setting the optical surface property of the CubeSat. The material's optical properties can be structured to reduce absorptivity and increase the CubeSat surface emissivity.
- I have designed a passive control method to keep the CubeSat cover and propellant tank temperatures within a predefined range by setting the surface optical properties and changing the solar panels' ratios.
- A quasi-LPV model has been derived in order to accomplish Model Predictive Control in (*Thesis 2*). The simulations showed that the differences between the simulation results of the integrated unified thermal model and the original thermal model are negligible under the same thermal conditions.

The simulation results have shown that the propellant tank temperatures ranged from *484 K to 501 K* for the case in which the CubeSat surface is made of uncoated aluminum. When I assumed a polished CubeSat surface with reflective metallic paint, the tank temperatures dropped, oscillating from *261 K to 266 K*. Furthermore, by simulating different solar panel ratios ($\lambda = 0.3$ *and* 0.7), the propellant tank temperatures contrasted from *265 K to 302 K*, which is within the propellant tank thermal operational limits.

Related publications: **[P1; P2; P4; P5]**

Thesis 2 *Thermal Control Approaches for a CubeSat* **(Chapter 3)**

I have designed different control schemes to track a constant reference temperature value and avoid the thermal fluctuations caused by the CubeSat's periodic motion on a low Earth orbit simultaneously. PID-based control structures have been used to track the propellant tank temperature along the satellite orbit, applying minimal essential power. As a further development, I have designed a linearization-based controller to maintain the propellant tank temperature at the reference temperature. An optimization-based model-predictive approach for the simultaneous design of an optimal solar panel ratio and a feasible control input sequence has also been proposed and evaluated.

- I have shown through simulations that the PID-based control system employing an anti-windup strategy keeps the propellant tank at a prescribed temperature value (*290 K*) throughout the satellite orbital. The anti-windup technique has avoided saturation and overshoot response and gave a suitable thermal response for the CubeSat propellant tank through the satellite orbital motion with the least amount of power consumption (*1.3 W*).
- The linearization method supplying the input/output linearization securing the feedback law to the nonlinear thermal model has been implemented for the thermal regulation of the CubeSat propellant tank. As a result, the linearization-based method adjusted the propellant tank temperature to the reference value with an acceptable thermal response and without additional power consumption (*1.5 W*).
- A novel multivariable model predictive control approach was developed which integrates the active and passive thermal control of the CubeSat using its quasi-LPV model. Both the solar area ratio and the heating power were considered inputs in the control scheme. The proposed approach can take into consideration several often contradictory goals and constraints related to power consumption and control performance.

The optimization modifications have revealed that if the temperature constraint of the CubeSat propellant tank is raised to *297 K*, the applicable sides of the CubeSat could be covered entirely by solar cells ($\lambda = 1$). So far, optimal solar panel percentages covering the specific faces of the CubeSat have varied from *44.8% to 100%* regarding the propellant tank thermal limit and the acceptable fluctuation of the thermal response of the CubeSat propellant tank through orbit.

Related publications: **[P2; P5; P6; P7; P8]**

Thesis 3 *Unmanned aerial vehicle navigation using GNSS/INS integration* **(Chapter 4)**

I have proposed a novel GNSS data prediction method which uses the K-Nearest Neighbor (KNN) algorithm for improving the data synchronization between the INS sensors and the GNSS receiver. This algorithm is also employed to produce the GNSS loss data. I have designed a reinforced and innovative ultra-tightly coupled approach to integrate the GNSS available data correlator with the INS's position, velocity, and attitude to rectify the INS measurements. I have illustrated the applicability of the approach for improving navigation performance in challenging environments through different scenarios using real measurement data.

- I have shown through computations that the proposed KNN predictor estimates the missing data between GNSS sampling instants with sufficient precision, which allows the successful synchronization with INS.
- I have shown that the navigation data can be enhanced using an ultra-tight integration approach, where the integration trajectories for the three axes track the GNSS received data in real-time.
- I have developed a simulation framework in Matlab to study four different integration scenarios containing data blocking situations of different lengths using real measurement data collected at the Mátyásföld airfield.

The obtained results have shown that the computed signals of the GNSS/INS integration yield more accurate position data when the GNSS signal is blocked. Moreover, the three axes GNSS standard deviation calculation ($X = 26.6793$, $Y = 115.8801$, $Z = 15.0102$) is smaller than the standard deviation calculation for GNSS/INS ($X = 27.4085$, $Y = 116.6536$, $Z = 15.5051$) when they are subjected to 8 seconds signal blocking period. However, the proposed integration technique is able to maintain sufficiently precise localization when GNSS signals are not available for 1, 4, or 8 seconds. This advantageous feature is guaranteed by the physical background of the applied KNN algorithm.

Related publications: **[P3; P9]**

5 Suggestions for future research

The design and operation of small satellite thermal control systems and integrated satellite navigation are complicated tasks involving a vast number of variables and multiple engineering disciplines. Given the encouraging results of this dissertation, we would like to extend the approaches and the results presented in these theses in the following directions.

Nonlinear dynamic thermal model. The dynamic thermal model in (Thesis 1) is an applicable thermal analysis tool for the CubeSat in its present configuration. It does, however, have certain restrictions. Therefore, it could be extended in a straightforward way to include the interplanetary trajectories of the CubeSat orbit instead of a circular motion and with an actual calculation of the Sun phase time and eclipse orbit duration. We can also make more complex mathematical models of the structure of the Cubesat and more sophisticated dynamic movements of a CubeSat in orbit by considering the actual movement of the satellite rather than just having face 3 of the CubeSat facing the Earth.

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Thermal Control Approaches. An important part of the whole design is the passive environment, which is essentially the surface composition and solar cell ratio of the faces. Therefore, future work will be focused on the optimization of these parameters to further reduce the necessary heating energy. The application of thermal active control strategies can be extended to various system designs, such as advanced control synthesis, adaptive control systems, or sliding mode control systems, exploiting the actual thermal model variables and inputs. An on-line MPC could be one of the important directions of research in the future. It simultaneously computes the optimized value of $lambda$, simulates the satellite's thermal performance, and controls the temperature at the same time.

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Navigation using GNSS/INS integration. The navigation strategies are directed toward improving the quality of the IMU sensors, and various sensor properties may be evaluated. Using different types of INS (low cost, medium cost, and high cost) and integrating each type of INS with GNSS. Then we would like to compare the results of integration between these three types of integration, in order to determine whether the integration of low-cost INS with GNSS affects the obtained results or not, for the purpose of using low-cost INS for the integration purpose with GNSS instead of medium or high-cost INS. More sophisticated error models may be used in the Kalman filter. The integration of GNSS/INS can be used, with a new filtering methodology, to achieve optimal noise filtering over the whole motion band of interest.

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The author's publications

Journal papers

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[P2] Nawar Al-Hemeary, Péter Polcz, and Gábor Szederkényi. Optimal solar panel area computation and temperature tracking for a cubesat system using model predictive control. *SPIIRAS Proceedings*, 19(3):564–593, 2020. DOI: `10.15622/sp.2020.19.3.4`.

[P3] Sameir A Aziez, Nawar Al-Hemeary, Ahmed Hameed Reja, Tamás Zsedrovits, and György Cserey. Using KNN Algorithm Predictor for Data Synchronization of Ultra-Tight GNSS/INS Integration. *Electronics*, 10(13):1513, 2021. DOI: `10.3390/electronics10131513`.

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[P4] Nawar Al-Hemeary and Gábor Szederkényi. Dynamic thermal simulation of the CubeSat. In: *PhD Proceedings Annual Issues of the Doctoral School Pázmány Péter Catholic University, Faculty of Information Technology and Bionics - 2018*. Ed. by P. Szolgay G. Prószéky. Vol. 13. 50/a Práter street, 1083 Budapest, Hungary: Pázmány University ePress, 2018, 32.

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[P8] Nawar Al-Hemeary and Gábor Szederkényi. PID-based temperature control of a small satellite. In: *PhD Proceedings Annual Issues of the Doctoral School Pázmány Péter Catholic University, Faculty of Information Technology and Bionics - 2019*. Ed. by P. Szolgay G. Prószéky. Vol. 14. 50/a Práter street, 1083 Budapest, Hungary: Pázmány University ePress, 2019, 87.

[P9] Nawar Al-Hemeary and Gábor Szederkényi. Construction of unmanned aerial vehicles applying INS / GPS navigation. In: *PhD Proceedings Annual Issues of the Doctoral School Pázmány Péter Catholic University, Faculty of Information Technology and Bionics - 2021*. Ed. by P. Szolgay G. Prószéky. Vol. 16. 50/a Práter street, 1083 Budapest, Hungary: Pázmány University ePress, 2021, 125.

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[P10] Nawar Al-Hemeary and Gábor Szederkényi. Thermal model development for a CubeSat. In: *5th international Ph.D. Workshop*. Veszprem: University of Pannon, doctoral school of information and technology, 2018.

[P11] Nawar Al-Hemeary and Gábor Szederkényi. Linearization-based thermal control design for a CubeSat. In: *Advanced ICT Tools and Methods for Cyber-Physical Systems and Biomedical Applications. Oral Presentation titled*. Esztergom: Pázmány University ePress, 2019.

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[P12] Riadh A. Kadhim, AL-Hemeary Nawar, Abdul Kareem K. Abdul, Liming Yuan, and Jiang Wu. Optical Fiber Refractive Index Sensor Based on the SPR Using a Multiple D-shaped Ag Nanowire. In: *2020 IEEE SENSORS*. 2020, 1–4. DOI: 10.1109/SENSORS47125.2020.9278803.

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