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DIGITAL MODELING AND PERFORMANCE ANALYSIS OF A STAR TRACKER FOR SMALL SPACECRAFT

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Abstract
This study presents a digital prototype of a star tracker for attitude determination of small spacecraft and establishes a basis for the subsequent development of a digital twin of the device. The developed model integrates the Hipparcos star catalog, spacecraft motion and attitude models, an optical projection model, synthetic image generation, noise models, star detection and identification algorithms, and attitude estimation based on Wahba's problem. A Monte Carlo approach with 500 independent trials for each investigated configuration was used to quantitatively evaluate the system performance. The effects of the number of stars used for attitude determination, the PSF parameter, readout noise, background and solar illumination, and spacecraft angular velocity were investigated. The results show that increasing the number of stars improves the reliability of attitude determination up to a certain level. For the investigated configuration, the use of 15 stars provided an 87% successful determination probability with an RMS attitude error of 0.0396°. Within the investigated range, a PSF standard deviation of $\sigma = 2.5$ pixels provided the lowest RMS attitude error of 0.0342° and the highest successful determination probability of 87%. Read noise, background illumination, and solar glare primarily reduced the number of detected stars, whereas spacecraft angular velocity had the strongest effect on overall performance. At an angular velocity of 6°/s, the successful determination probability decreased to 14%, while no successful attitude determination was obtained at 8°/s and above. The obtained results provide a basis for selecting star tracker parameters, optimizing its algorithms, validating the model against a physical prototype, and further developing the digital prototype into a digital twin.
Keywords: star tracker, digital prototype, small spacecraft, attitude determination, Monte Carlo simulation.
Conflict of Interest: The authors declare that there is no conflict of interest.

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ШАҒЫН ҒАРЫШ АППАРАТТАРЫНА АРНАЛҒАН ЖҰЛДЫЗДЫҚ БАҒЫТТАУ ЖҮЙЕСІН ЦИФРЛЫҚ МОДЕЛЬДЕУ ЖӘНЕ ӨНІМДІЛІГІН ТАЛДАУ

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Аннотация. Бұл зерттеуде шағын ғарыш аппараттарының бағдарын анықтауға арналған жұлдыздық бағыттау жүйесінің цифрлық прототипі ұсынылып, құрылғының кейінгі цифрлық егізін әзірлеуге негіз қаланды. Әзірленген модельде Hipparcos жұлдыздар каталогы, ғарыш аппаратының қозғалысы мен бағдарын модельдеу, оптикалық проекция моделі, синтетикалық кескіндерді қалыптастыру, шу модельдері, жұлдыздарды анықтау және сәйкестендіру алгоритмдері, сондай-ақ Вахба есебіне негізделген бағдарды бағалау әдісі біріктірілген. Жүйенің өнімділігін сандық бағалау үшін әрбір зерттелетін конфигурация бойынша 500 тәуелсіз сынақтан тұратын Монте-Карло әдісі қолданылды. Бағдарды анықтау үшін пайдаланылатын жұлдыздар санының, PSF параметрінің, оқу шуының, фондық және Күн сәулесінің жарықтануының, сондай-ақ ғарыш аппаратының бұрыштық жылдамдығының әсері зерттелді. Нәтижелер жұлдыздар санын арттыру бағдарды анықтаудың сенімділігін белгілі бір шекке дейін арттыратынын көрсетті. Зерттелген конфигурацияда 15 жұлдызды пайдалану бағдарды 87% ықтималдықпен сәтті анықтауға мүмкіндік берді, бұл ретте бағдардың орташа квадраттық қателігі 0.0396° болды. Зерттелген диапазонда PSF стандартты ауытқуы σ = 2.5 пиксель болған кезде бағдардың ең төменгі орташа квадраттық түбірлік қателігі 0.0342° және бағдарды сәтті анықтаудың ең жоғары ықтималдығы 87% алынды. Оқу шуы, фондық жарықтану және Күннің жарқылы негізінен анықталған жұлдыздар санын азайтты, ал ғарыш аппаратының бұрыштық жылдамдығы жүйенің жалпы өнімділігіне ең күшті әсер етті. Бұрыштық жылдамдық 6°/с болған кезде бағдарды сәтті анықтау ықтималдығы 14%-ға дейін төмендеді, ал 8°/с және одан жоғары жылдамдықтарда бағдарды сәтті анықтау байқалмады. Алынған нәтижелер жұлдыздық бағыттау жүйесінің параметрлерін таңдауға, оның алгоритмдерін оңтайландыруға, модельді физикалық прототиппен валидациялауға және цифрлық прототипті одан әрі цифрлық егізге айналдыруға негіз болады.

Түйін сөздер: жұлдыздық датчик, цифрлық прототип, шағын ғарыш аппараты, бағдарды анықтау, Монте-Карло әдісімен модельдеу.
Мүдделер қақтығысы: авторлар мүдделер қақтығысының жоқ екенін мәлімдейді.

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ЦИФРОВОЕ МОДЕЛИРОВАНИЕ И АНАЛИЗ ХАРАКТЕРИСТИК ЗВЕЗДНОГО ДАТЧИКА ДЛЯ МАЛЫХ КОСМИЧЕСКИХ АППАРАТОВ

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Аннотация. В настоящем исследовании представлен цифровой прототип звездного датчика для определения ориентации малых космических аппаратов и заложена основа для последующей разработки цифрового двойника устройства. Разработанная модель объединяет каталог звёзд Hipparcos, модели движения и ориентации космического аппарата, модель оптического проецирования, генерацию синтетических изображений, модели шумов, алгоритмы обнаружения и идентификации звезд, а также оценивание ориентации на основе задачи Вахбы. Для количественной оценки характеристик системы использовался метод Монте-Карло с 500 независимыми испытаниями для каждой исследуемой конфигурации. Были исследованы влияния количества звёзд, используемых для определения ориентации, параметра PSF, шума считывания, фонового и солнечного освещения, а также угловой скорости космического аппарата. Результаты показывают, что увеличение количества звёзд повышает надёжность определения ориентации до определённого уровня. Для исследованной конфигурации использование 15 звезд обеспечило вероятность успешного определения ориентации 87% при среднеквадратичной ошибке ориентации 0.0396°. В исследованном диапазоне стандартное отклонение PSF σ = 2.5 пикселя обеспечило наименьшую среднеквадратичную ошибку ориентации 0.0342° и наибольшую вероятность успешного определения ориентации – 87%. Шум считывания, фоновое освещение и солнечная засветка преимущественно приводили к уменьшению количества обнаруживаемых звезд, тогда как угловая скорость космического аппарата оказывала наиболее сильное влияние на общие характеристики системы. При угловой скорости 6°/с вероятность успешного определения ориентации снизилась до 14%, тогда как при скорости 8°/с и выше успешное определение ориентации не было получено. Полученные результаты создают основу для выбора параметров звездного датчика, оптимизации его алгоритмов, валидации модели на физическом прототипе и дальнейшего развития цифрового прототипа в цифровой двойник.
Ключевые слова: звездный датчик, цифровой прототип, малый космический аппарат, определение ориентации, моделирование методом Монте-Карло.
Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction

The rapid growth of small-spacecraft and small-satellite technologies has increased the need for compact, autonomous, and precise attitude-determination systems. Knowledge of attitude of spacecraft is crucial for many space missions such as Earth observation, astronomical observation, communications, navigation, and spacecraft autonomy [1, 2]. In this regard, star trackers are widely regarded as highly accurate autonomous sensors for absolute attitude determination because they rely on the observed positions of stars within their field of view [3]. However, the performance of a star tracker depends on the combined characteristics of its optical system, image sensor, image-processing algorithms, star-identification method, and spacecraft motion conditions [4].

A typical star tracker is an electro-optical system made up of four main functional subsystems: a stray-light baffle, an optical system, a photosensitive detector, and an electronic and image-processing unit [5]. The baffle serves to block radiation coming from bright off-axis sources such as the Sun, the Earth, and the Moon, and the optical system projects the images of the stars onto the detector [6]. The detector then turns the optical radiation into a digital image, after which the onboard electronics process this image. The image-processing chain usually involves estimating the background, detecting the stars and determining the position of their centres, identifying the star pattern by comparing it with a catalogue stored on board, and finally estimating the attitude from the inertial star vectors that have been identified [7]. This design enables the star tracker to give autonomous three-axis attitude information without the need for an external attitude reference [8]. Yet the system's overall performance is determined by the way in which its optical, detector, computational, and environmental characteristics interact.

A wide variety of commercial star trackers is currently available for spacecraft, offering different combinations of mass, power consumption, accuracy, field of view, and dynamic performance. Examples of such devices are the ST200 and ST400 series made by Berlin Space Technologies, the Standard NST and Full-Extension NST from Blue Canyon Technologies, CubeStar from CubeSpace, the ASTRO CL and ASTRO APS/APS3 from Jena-Optronik, Spacestar from Leonardo, among others [9-16]. Although much progress has been made in terms of miniaturization and precision, one major issue that is still a problem is that of achieving precision in attitude, low weight and power consumption, and operation in conditions of stray light, noise, and spacecraft movement [17].

Several investigations have been carried out to improve star tracker performance in accuracy, reliability, miniaturization, and computational speed for spacecraft attitude control. These investigations have considered a number of different issues in regard to the design and operation of star trackers, such as optical system design, stray light reduction, star recognition algorithms, and others. Erlank and Steyn developed a CubeSat-compatible nano star tracker that demonstrated autonomous attitude estimation at 1 Hz and attitude accuracy better than 0.01° during night-sky tests, showing the feasibility of miniaturized star trackers for small spacecraft [18]. Sun et al. proposed a direct astronomical observation method to evaluate star-tracker accuracy and demonstrated pointing and rolling accuracies of 3.33'' and 23.96'', respectively, at the 3σ level, using about 18,000 s of real-sky observations [19]. Asadnezhad et al. demonstrated the importance of optical design and stray-light suppression by developing a star-tracker optical system with a 14° field of view and an RMS spot size below 4 μm, and their baffle design reduced simulated stray light by approximately 11 orders of magnitude [20]. Sang et al. demonstrated a CMOS-based nano star tracker with a mass of 150 g, a power consumption of approximately 0.85 W, and a pointing accuracy of about 5'', demonstrating the feasibility of combining arcsecond-level performance with strong miniaturization for spacecraft applications [21]. However, these studies primarily focus on individual aspects of star-tracker performance, such as miniaturization, optical design, measurement accuracy, or hardware implementation. A unified digital evaluation of the combined effects of star count, image quality, detector noise, background illumination, and spacecraft angular velocity remains comparatively limited.

The development and qualification of a high-precision star tracker typically involves several stages, including hardware design, laboratory testing, calibration, and environmental testing [22]. Even though physical testing is necessary for final verification, it is very resource-consuming and does not generally enable the examination of a large number of combinations of optical, tracker, environmental, and dynamic parameters in the early stages of development. Specifically, detector noise, background illumination, optical image quality, the number of stars that can be observed, exposure time, and spacecraft angular motion all tend to interact and affect the overall performance of attitude

determination. Digital modelling acts as a useful complementary method since it replicates the main functional chain of a star tracker in a single computational environment [23]. The model includes the generation of the stellar field, the optical projection onto the focal plane, the formation and degradation of the stellar images, the detection of the stars and the estimation of their centroids, the identification of the stars by means of a reference catalogue, and the final determination of the spacecraft's attitude. With this approach we are able to systematically vary various parameters and operating conditions in order to find out which parameters are sensitive, what the critical operating conditions are, and what the performance limitations are before building a physical prototype. In the current study the model developed is considered to be a digital prototype not a full digital twin since it has not yet attained continuous bidirectional synchronisation with a physical star tracker [24]. However, the digital prototype does provide a foundation for performance analysis and parameter optimisation, and it can be verified using experimental data before being further developed into a digital twin of the physical system.

This study aims to develop and test a digital prototype of a star tracker for small spacecraft and quantitatively evaluate how key optical, image-quality, and dynamic parameters affect attitude-determination performance. The main contributions of this study are as follows:

– development of an integrated digital prototype that combines stellar-field generation, optical projection, image degradation, star detection, star identification, and attitude estimation;

– quantitative evaluation of the effects of star count, PSF width, detector read noise, background illumination, and solar glare using Monte Carlo simulations;

– quantitative assessment of the effect of spacecraft angular velocity during image exposure on star-identification and attitude-estimation performance.

Methodology

Digital Prototype Architecture

The performance of the star tracker was investigated using an integrated digital prototype that reproduces the main stages of the attitude determination process. The model consists of interconnected modules for stellar catalogue processing, spacecraft attitude and motion modelling, optical projection, stellar image generation, image degradation, star detection, star identification, and attitude estimation (Fig. 1). This integrated structure allows evaluation of individual parameters while preserving the full processing chain from the observed stellar field to the final attitude solution. The developed model is considered a digital prototype rather than a complete digital twin because it does not provide continuous bidirectional synchronization with a physical star tracker.

The Hipparcos catalogue was used as the primary source of stellar positions and apparent magnitudes. Two catalogue subsets were used in the simulations. The stellar field generation model included stars with an apparent magnitude of $V_{mag} \leq 6$, resulting in 5041 stars. A reduced catalogue containing 1625 stars with $V_{mag} \leq 5$ was used as the reference catalogue for the star-identification procedure in order to reduce the computational load. The right ascension and declination of each star were converted into three-dimensional unit direction vectors for subsequent coordinate transformations and attitude calculations.

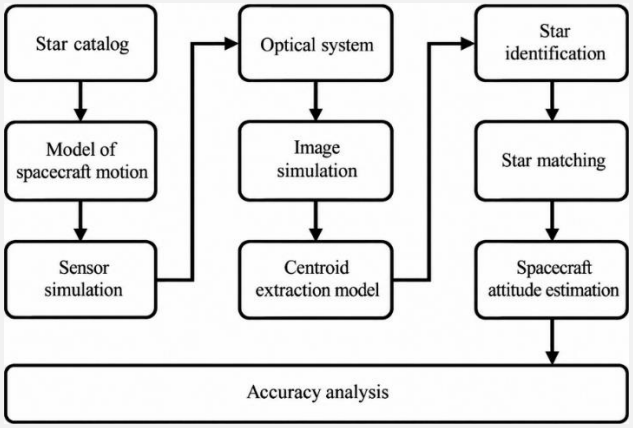


Figure 1. General architecture and processing sequence of the proposed digital prototype

The transformation from equatorial coordinates to a unit direction vector is defined as [25]:

$$s = \begin{bmatrix} \cos\delta\cos\alpha \\ \cos\delta\sin\alpha \\ \sin\delta \end{bmatrix}, \quad (1)$$

where α is the right ascension and δ is the declination of the star.

The principal parameters of the digital prototype are summarized in Table 1.

Table 1 – Main parameters of the model

№	**Parameter**	**Value**
1	Star catalogue	Hipparcos
2	Catalogue limit for image generation	$V_{mag} \leq 6$
3	Number of stars	5041
4	Reference catalogue limit	$V_{mag} \leq 5$
5	Reference catalogue size	1625
6	Field of view	20°
7	Focal length	35 mm
8	Detector resolution	1024 × 1024 pixels
9	Pixel size	20 μm
10	Baseline PSF	σ = 2.5 pixels
11	Exposure time	0.1 s
12	Monte Carlo trials	500

Optical Projection and Stellar Image Formation

A simplified projection approach was used to model the optical subsystem. The field of view of the star tracker was 20◦ allowing multiple stars to be observed simultaneously. The focal length was fixed at 35 mm, while the detector was considered to be 1024×1024 pixels of size 20 μm. The above values were chosen as the reference for further computations. After transformation into the tracker coordinate system, only stars located within the field of view were included in the image generation process. Their direction vectors were projected onto the focal plane according to [26]:

$$x = f\frac{x_b}{z_b}, \quad (2)$$

$$y = f\frac{y_b}{z_b}, \quad (3)$$

where f is the focal length, x_b, y_b, z_b are the components of the star direction vector. The focal-plane coordinates were subsequently converted into detector pixel coordinates.

A two-dimensional Gaussian point spread function (PSF) was used to model the spatial distribution of stellar intensity over adjacent detector pixels resulting from the combined effects of the optical system and detector. The intensity distribution was represented as [27]:

$$I(x,y) = I_0 \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2}\right), \tag{2.30}$$

where I_0 is the peak stellar intensity, (x_0, y_0) is the image-centre coordinate, and σ is the spatial width of the stellar image. The baseline value was set to σ = 2.5 pixels. To investigate the sensitivity of the system to image quality, σ was subsequently varied between 2.0 and 3.5 pixels.

Image Degradation and Star Detection

To simulate non-ideal observation conditions, the stellar images generated initially were altered. The three main degradation factors examined were detector readout noise, background illumination, and solar glare. Each of these factors was added separately while the other model parameters stayed at their baseline values. The reason for adopting this method was to find out how they affected star detection, the reliability of star identification, and the final attitude solution. Before carrying out star detection, an estimate of the slowly varying background component was obtained by means of a Gaussian filter having a standard deviation of 50 pixels. This estimated background was subtracted from the original image. An adaptive threshold was then applied to the corrected image in order to distinguish the stellar objects from the remaining background fluctuations. Connected-component analysis was employed to identify the individual stellar objects. The image coordinates of these objects were determined using a centroid method which took intensity into account. This process yielded the measured star positions needed for the next identification stage.

Star Identification and Attitude Estimation

The detected stellar objects were identified by means of the Triangle Hash pattern-recognition algorithm. This algorithm determines the correspondence between the detected stars and those in the reference catalog by means of the geometrical relationships between them. The employment of geometrical relationships enables the identification of the stars without regard to the absolute orientation of the spacecraft. After successful identification, each star that had been observed was represented by a measured unit vector in the tracker coordinate system and by a corresponding reference unit vector in the inertial coordinate system; these vector pairs were then used for attitude determination. A trial was considered successful when the star-identification stage produced a valid set of star correspondences and a corresponding attitude solution satisfying the predefined success criterion.

The spacecraft attitude was estimated by solving Wahba's problem, which determines the rotation providing the best correspondence between the measured and reference star vectors. The corresponding objective function can be written as [28]:

$$L(A) = \frac{1}{2}\sum_{i=1}^{n} w_i \left\| y^b_{meas.,i} - A y^i_i \right\|^2, \tag{1.2}$$

where $y^b_{meas.,i}$ is the measured unit vector, y^i_i is its corresponding reference vector, A is a rotation matrix defining the attitude, w_i is the weight assigned to the i-th star, n is the number of identified stars.

Monte Carlo Simulation and Evaluation Metrics

The performance of the digital prototype has been estimated through the Monte Carlo method. For each setting of parameters under analysis, 500 simulation experiments have been performed. The same number of independent trials was used for each parameter value to ensure consistent comparison between the investigated configurations. In each of them, a random initial attitude of the spacecraft was selected and then its stellar field was simulated and passed through the entire chain of the star tracker system. This procedure was applied to all investigated optical, noise, and dynamic conditions. The

system performance was evaluated using several quantitative metrics. The successful attitude determination probability was calculated as:

$$P_{success} = \frac{N_{success}}{N_{total}} \times 100\%, \quad (3)$$

where $N_{success}$ is the number of successful trials and N_{total} is the total number of Monte Carlo trials. The angular attitude error was calculated for each successful trial by comparing the estimated attitude with the reference attitude. The root mean square error (RMSE) was then determined as [29]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N} e_k^2}, \quad (8)$$

where e_k is the angular attitude error of the k-th successful trial and N is the number of successful trials. Apart from the success probability and RMSE, the mean angular error is additionally estimated to estimate the average attitude estimation accuracy. As far as noise experiments are concerned, the average number of found stars is additionally used as another indicator of image degradation. In turn, as far as dynamic experiments are concerned, the average number of correctly verified star pairs is additionally taken into account. Such additional parameters provide an opportunity to separate the impact of image degradation and spacecraft motion on the attitude estimation error.

Dynamic Motion Model

The impact of the rotational movement of the space probe was examined by setting a fixed value for the angular velocity while image exposure. The angular velocity was varied from 0 to 10°/s, while the exposure time was fixed at $T_{\text{exp}} = 0.1$ s. The angular displacement of the spacecraft during one exposure was therefore determined by:

$$\Delta\theta = \omega T_{\text{exp}}, \quad (9)$$

where ω is the spacecraft angular velocity. The resulting displacement of the stellar images during exposure was used to represent motion-induced image blur. The displacement of the stars caused by such movement during image exposure was used as the model of image blur caused by motion. For instance, at an angular velocity of 10° per second and an exposure time of 0.1 seconds, there is a 1° rotation of the spacecraft during one exposure. For each angular-velocity value, 500 separate images were created and processed using the entire digital system.

The software code used to develop the digital prototype was written using Python coding language in Visual Studio Code development environment. The PyQt6 and PyQtGraph libraries were used in developing the graphical user interface and 3D visualizations, respectively.

Results and Discussion

A three-dimensional model was developed to enable visual monitoring of the digital prototype's operation and to verify the correctness of the algorithms (Fig. 2).

Effect of the Number of Stars on Attitude Determination Performance

The first series of experiments investigated the influence of the number of stars used for attitude determination on the performance of the digital prototype. The obtained results are summarized in Table 2. It was found that the performance of attitude determination depended strongly on the number of stars available. When 5 stars were available, the probability of a successful determination was only 15%, the RMS error being 0.0479°. Increasing the number to 7 and then to 10 stars raised the success rate to 72% and 84% respectively, and at the same time reduced the RMS error to 0.0428° and 0.0406°.

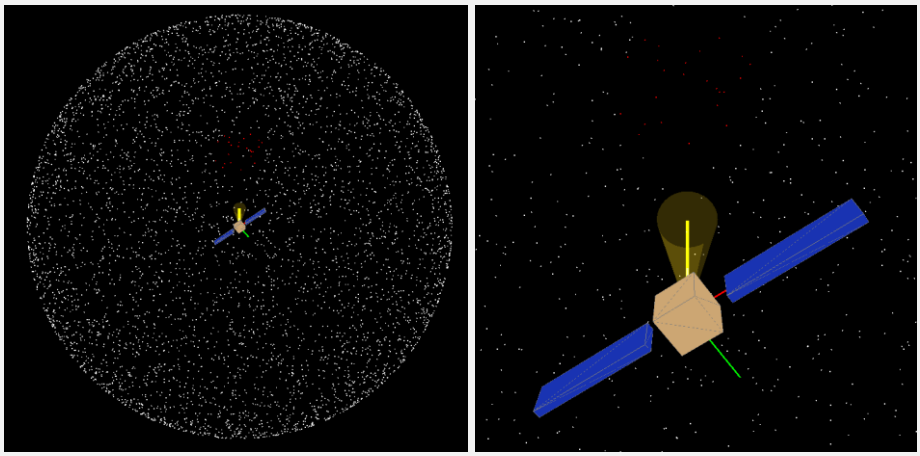


Figure 2. Three-dimensional image of the digital prototype

Table 2. Effect of the number of stars on attitude determination performance

№	Number of stars	Successful determination, %	Mean error, °	RMS error, °
1	5	15	0.0453	0.0479
2	7	72	0.0387	0.0428
3	10	84	0.0373	0.0406
4	15	87	0.0359	0.0396
5	20	78	0.0385	0.0427

The best performance within the investigated range was obtained with 15 stars, yielding a successful determination probability of 87% and an RMS attitude error of 0.0396°. When the number of stars was increased to 20, the successful determination probability decreased to 78% and the RMS error increased to 0.0427°. Thus, within the investigated configurations, 15 stars provided the best observed combination of successful determination probability and attitude accuracy.

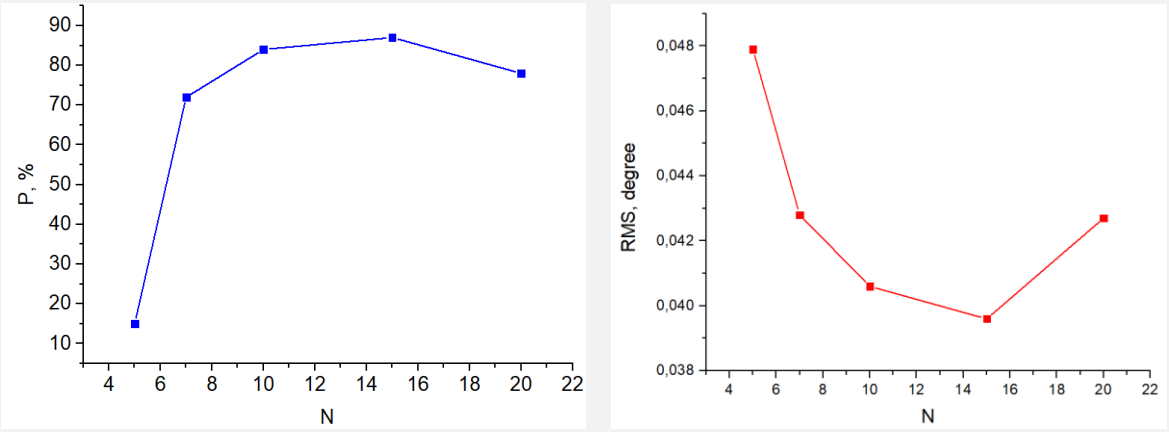


Figure 3. Dependence of the successful attitude determination probability (A) and RMS attitude error (B) on the number of stars used

Effect of the Point Spread Function on Attitude Accuracy

The second series of experiments examined the influence of the point spread function (PSF) on the accuracy of attitude determination. The stellar images were generated using a Gaussian PSF, and its standard deviation σ was varied from 2.0 to 3.5 pixels. The results are presented in Table 3.

The results indicate that there is a non-linear correlation between the PSF width and attitude determination accuracy. For a value of σ equal to 2.0 pixels, the probability of a successful determination was 85%, with an RMS error of 0.0358°.

Table 3. Effect of the PSF parameter on attitude determination accuracy

№	PSF standard deviation, σ, pixels	Successful determination, %	Mean error, °	RMS error, °
1	2.0	85	0.0326	0.0358
2	2.5	87	0.0325	0.0342
3	3.0	75	0.0381	0.0435
4	3.5	64	0.0440	0.0630

As the PSF width increased to σ = 2.5 pixels, there was an improvement, where the probability of a successful determination increased to 87% and the RMS error decreased to 0.0342°. However, an increase in σ further to 3.0 and 3.5 pixels led to a decrease in the probability of a successful determination to 75% and 64%, with the RMS error increasing to 0.0435° and 0.0630°, respectively. This trend can be explained by the broader spatial distribution of stellar intensity at larger PSF widths. As the stellar energy is distributed over a larger number of pixels, the peak intensity decreases, which can reduce centroiding accuracy and increase the probability of interference between nearby stellar images. Although σ = 2.5 pixels led to the best performance within the range of values investigated, it is specific to the digital prototype used. Fig. 4 shows the effect of the PSF parameter on the probability of successful orientation determination and the root-mean-square error of orientation determination.

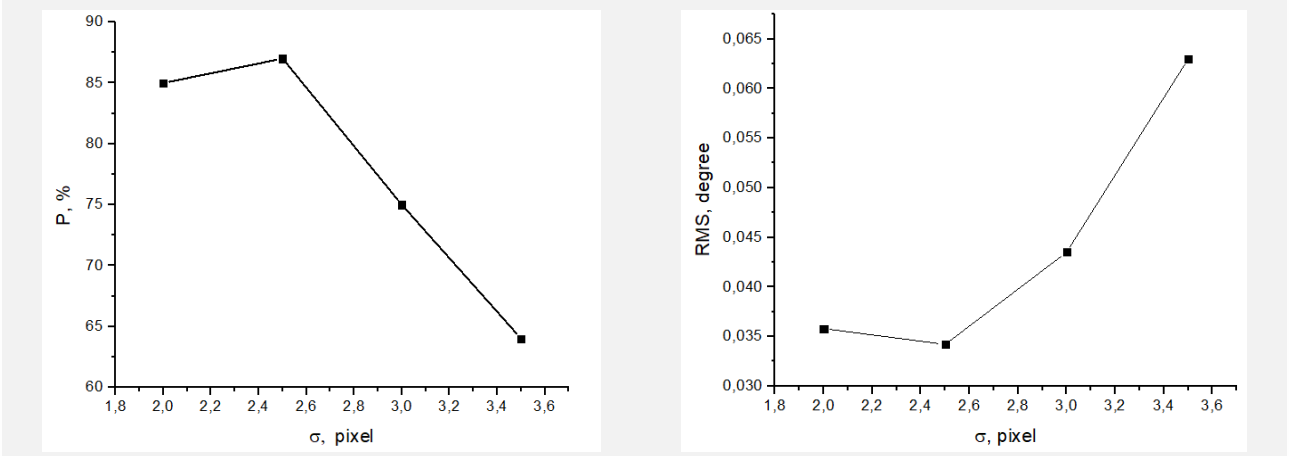


Figure 4. Dependence of the successful attitude determination probability (A) and RMS attitude error (B) on the PSF standard deviation

Effect of Read Noise, Background Illumination, and Solar Glare

The third series of experiments investigated the influence of image degradation factors on the performance of the digital prototype. Three factors were considered independently: detector read noise, background illumination, and solar glare. The evaluated parameters included the successful attitude determination probability, RMS error, mean angular error, number of detected stars, and number of verified star pairs.

Read Noise. The read noise was varied from 0 to 10 normalized model units. These values represent normalized simulation parameters rather than experimentally calibrated detector noise levels. Within this range, no pronounced degradation in attitude accuracy was observed: the RMS error remained at 0.035-0.044°, while the successful determination probability varied between 79% and 90%. However, the average number of detected stars decreased from 39.36 to 31.48, corresponding to a reduction of approximately 20%. Despite this decrease, the number of verified star pairs remained approximately 7-8. Thus, moderate read noise primarily affected star detection, while the remaining reliable star correspondences were sufficient to maintain stable attitude estimation.

Background Illumination. The normalized intensity of background illumination was varied from 0 to 10. The higher values of background intensity affected the star detection because the average number of detected stars decreased from 45.43 to 33.03 or 27%. In any case, the RMS error was within 0.036° and 0.045°, and the success probability ranged from 76% to 89%, not having any monotonous dependence on the background illumination level. The number of verified star pairs was usually

maintained between 7 and 8. So, it follows from the analysis conducted that the higher background illumination decreases the number of detected stars but does not significantly influence the attitude determination accuracy.

Solar Glare. The effect of solar glare was studied by varying the normalized solar-glare parameter from 0 to 10. The RMS error stayed between 0.034° and 0.044°, and the probability of successfully determining the stars varied from 80% to 89%, there being no obvious relationship between this probability and the level of glare. The average number of stars detected fell from 43.19 when Sun Glare was 0 to 33.89 when Sun Glare was 10, which amounts to a reduction of about 21.5%. Nevertheless, the number of verified star pairs stayed mostly between 7 and 8, showing that the remaining stars were enough to keep attitude estimation stable under the conditions examined. The results are shown in Fig. 5.

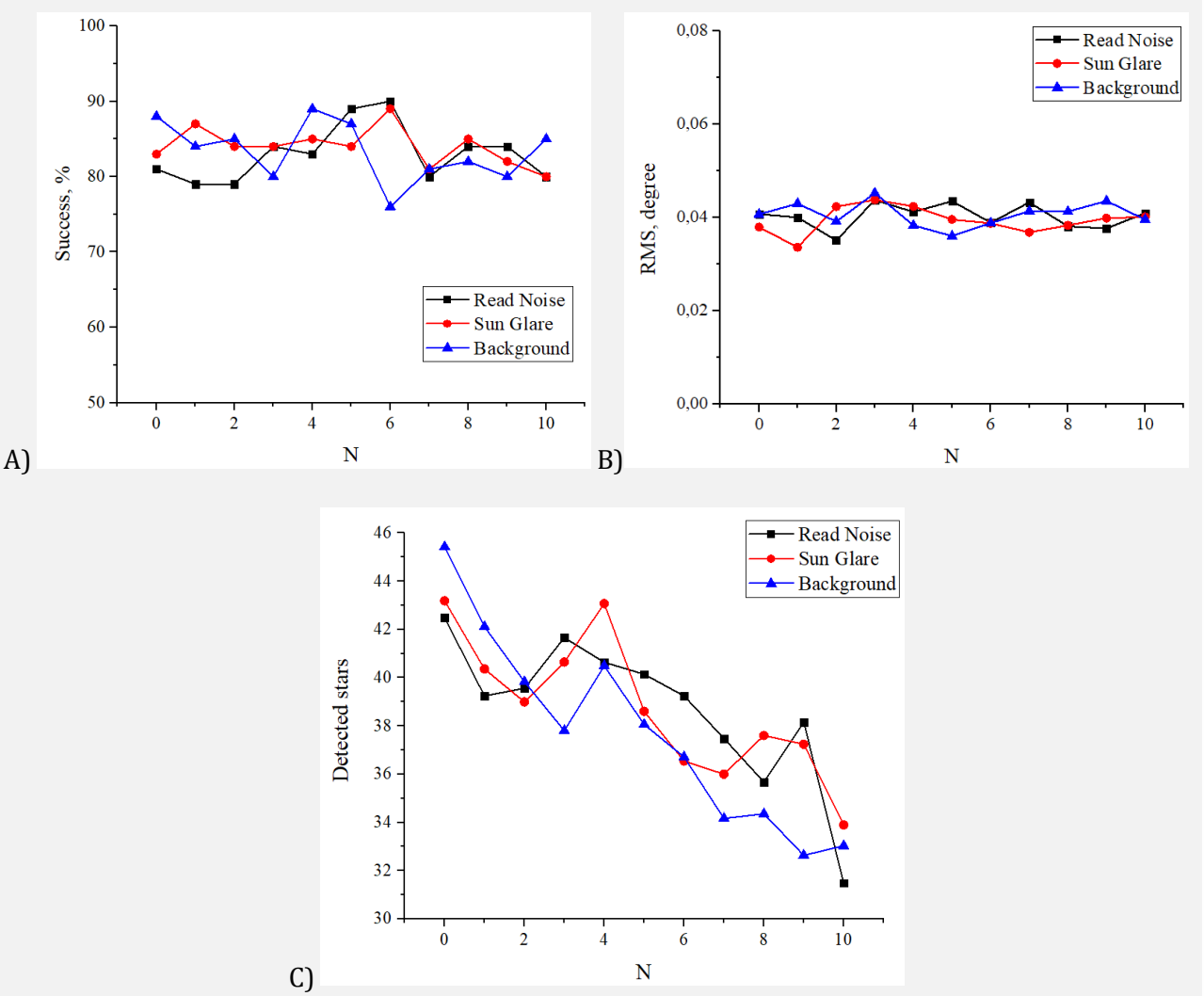


Figure 5. Effect of various types of noise on the star tracker accuracy:
A – determination probability; B – RMS error; C – detected stars.

For the investigated ranges and the adopted noise models, read noise, background illumination, and solar glare primarily affected the number of detected stars, while their influence on attitude accuracy remained comparatively small. The number of stars detected reduced by 20%, 27% and 21.5% accordingly, but the number of identified pairs and attitude accuracy remained almost the same. Thus, within the investigated parameter ranges, a reduction in the number of detected stars did not necessarily lead to failure of attitude determination, provided that sufficient geometrical information remained available for reliable star identification. But, it is true only for the given values of parameters

and noise models. Any other more severe or combined disturbances, along with optical and detector imperfections, would cause a higher level of degradation.

Effect of Spacecraft Angular Velocity

The final experiment investigated the influence of spacecraft angular velocity on star tracker performance (Fig. 6). Unlike the previous experiments, which primarily considered static attitude conditions, this experiment introduced spacecraft rotation during image exposure.

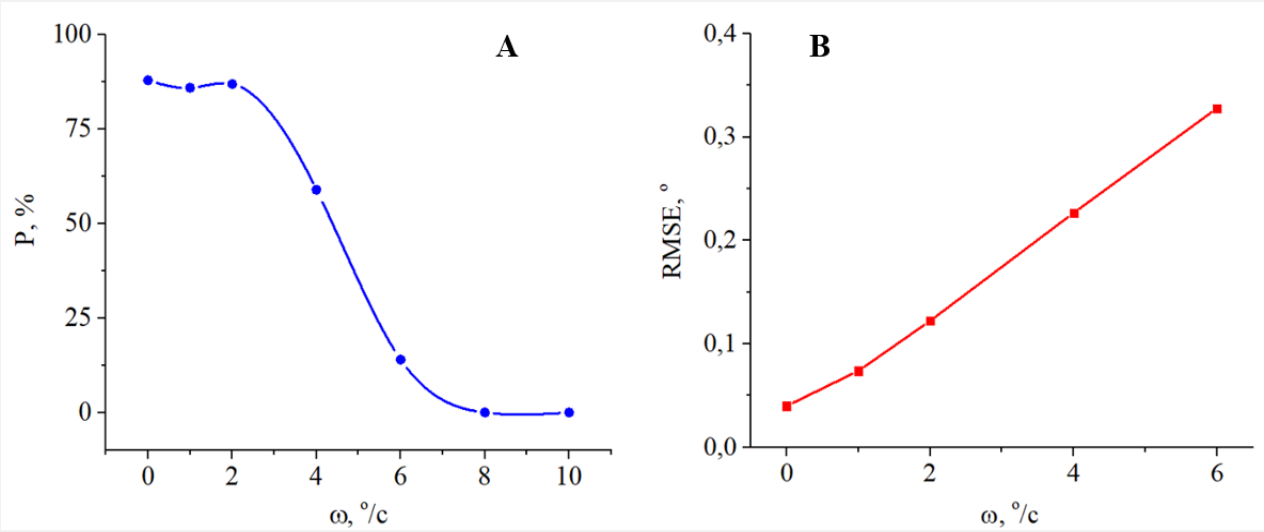


Figure 6. Effect of spacecraft angular velocity on star tracker performance: (A) successful attitude determination probability; (B) RMS attitude error

From the results obtained, it is clear that the performance of the star tracker is greatly dependent on the angular velocity of the spacecraft. In the static case, the probability of attitude determination is 88%, while the RMS error is 0.04000°. At low angular velocities of 1–2°/s, the successful determination probability remained close to the static case, although the RMS attitude error increased noticeably. At higher angular velocities, both the successful determination probability and attitude accuracy degraded substantially. At an angular speed of 4°/s, the success probability reduces to 59%, the RMS error increases to 0.22672°, and the number of verified star pairs reduces to 5.01. The most dramatic effect on the performance of the star tracker was witnessed when the angular speed was 6°/s, where the success rate reduced to 14%, the RMS error increased to 0.32792°, which is about 8.2 times the static case, and only 1.16 star pairs could be verified. No success was recorded when the angular speeds were 8°/s and 10°/s.

The key reason for the described degradation is blurring of the image of the star due to its movement over the course of the 0.1 s exposure time. The higher the angular velocity is, the larger the displacement of the star image on the focal plane will be and the more the performance of centroid calculation and star recognition will suffer from it. Unlike the noise-related parameters previously examined, that mostly had a tendency to decrease the number of stars detected, the movement of the spacecraft affected the quality of star correspondences as well as of the attitude determination itself. It is necessary to consider angular velocity, exposure time, detector and image processing parameters simultaneously when designing the system. This effect could be mitigated by decreasing the exposure time or through compensating for the motion and correcting the images, though there are compromises to be made in photon collecting efficiency and computational effort.

These four experimental groups demonstrate that the investigated factors affect different stages of the star-tracker processing chain. The number of stars and PSF affect identification and centroiding, moderate noise primarily affects the number of detected stars, while spacecraft angular velocity has the strongest negative effect on overall attitude-determination performance. In general, these experiments have demonstrated the usefulness of the digital prototype for isolating the effects of image quality, star identification, and spacecraft dynamics on attitude-determination accuracy.

While the digital prototype offers a comprehensive tool for analysis of the star tracker, there are a number of limitations that must be taken into account in the interpretation of the findings. The principal limitations include the lack of validation against a physical star tracker, the absence of bidirectional interaction with a real device, the independent variation of parameters rather than their simultaneous variation, and the fixed exposure time of 0.1 s. In addition, the noise and illumination parameters are represented using normalized simulation units rather than experimentally calibrated detector quantities. Therefore, the obtained performance values and threshold conditions should be interpreted as configuration-specific simulation results rather than direct hardware performance limits.

Conclusion

This study developed a digital prototype of a star tracker for small spacecraft and evaluated its performance under different numbers of observed stars, PSF widths, image-degradation conditions, and spacecraft angular velocities. The proposed model simulated all the main steps of the algorithm from generation of stellar field and formation of optical image to detection and identification of stars and attitude determination by solving Wahba's problem. The results show that the number of stars and PSF width significantly affect attitude-determination performance. Within the investigated configurations, 15 stars provided the highest successful determination probability of 87% with an RMS attitude error of 0.0396°, while a PSF standard deviation of σ = 2.5 pixels provided the lowest RMS error of 0.0342° and a successful determination probability of 87%. Read noise, background illumination, and solar glare primarily reduced the number of detected stars, while their influence on attitude accuracy remained comparatively small within the investigated parameter ranges. However, spacecraft rotational speed caused the greatest degradation: the RMS error rose from 0.04000° in the static experiment to 0.32792° at 6°/s, and no successful attitude determination was obtained at 8°/s and 10°/s. Overall, the results demonstrate that the proposed digital prototype can be used to systematically investigate the sensitivity of star-tracker performance to optical, image-quality, and spacecraft-dynamics parameters. Future work will focus on evaluating combined environmental and dynamic effects, optimizing exposure time and image-processing algorithms, and validating the model using a physical star-tracker prototype.

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