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A REVIEW ON GYROSTABILIZED SYSTEMS

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Abstract. *Many system designs have stability as a fundamental requirement. Gyrostabilization emerges as a natural solution for such systems, whose applications range from military to cinematography. Over the years, several studies have been carried out in order to improve their performance. However, the technology associated with electronic devices' processing power and the measurement of signals has evolved significantly, which leaves room for new studies. In this context, this research seeks to show the advances, the still existing limitations and the trends associated with gyrostabilized systems found in the literature in recent years. Through a systematic literature review, articles are selected for further analysis. The works are categorized according to the focus of the respective research. The review presents the main topics found in each selected research as control strategy, control schemes, technological advances and algorithms. Finally, conclusive analyzes are carried out, meeting the objective of this research.*

Keywords: *gyrostabilized systems, limitations, systematic literature review, technological advances, trends*

1. INTRODUCTION

Gyrostabilized systems play a key role in a wide range of applications, including: military, aerospace, offshore, robotics, photography, among others.

The study of gyrostabilization has been done for a long time, often with the aim of improving the performance of such systems or finding new applications, given the technological evolutions that have occurred over time.

There are several studies on gyrostabilization. One of the most extensive and complete is that done by Hilkert (2008). In it, the author introduces concepts and principles associated with inertial stabilized platforms (ISP), addressing aspects such as requirements, typical control configurations for line-of-sight (LOS) maintenance, bandwidth, structural interactions, misalignments, disturbances that cause inertial rotation of the LOS, alternative techniques for stabilization, components commonly used in ISP and their design tradeoffs.

Other studies focus on specific applications associated with that subject. An example is the work of Mulla and Vasambekar (2016), which gives an overview on the development and applications of control systems for antennas. In it, the authors list the potential use of some technologies in this specific application, such as solar energy as an alternative energy source and new algorithms to improve system performance in terms of speed, bandwidth, gain margin, phase margin and stability. They also point out the need for advanced radio frequency (RF) detector chips to improve the accuracy of signal detection, as well as the use of precision gears, sensors and motors with microstepping techniques to improve the accuracy of antenna positioning. Other needs pointed out by the authors are: low-cost computational simulators to test antennas and their system control algorithms and low-cost, low-power, small microcontrollers with graphic user interfaces (GUI) designed using visual programming languages. This exemplifies the need for continuous development of technologies associated with gyrostabilization.

In this sense, considering that the concepts, principles and results of such studies represent the context of the time in which they were published and that the technology is evolving over time, the search for new trends and research that promote the improvement of performance of gyrostabilized systems is justified.

Thus, the present article aims to provide a comprehensive overview of recently published articles on gyrostabilized systems, emphasizing the key findings and methodologies of selected articles in a systematic way. In addition, trends and opportunities for improvement that still exist are sought through the analysis of such articles.

2. METHODOLOGY

To carry out the intended study, the methodology described by Khan *et al.* (2003) was employed. The scientific study aims to answer the following question: What advances have been made and what are the trends and limitations that still exist in gyrostabilized systems?

An adaptation of the research process described by that author is represented in Fig. 1, composed of steps, actions and tools, in order to facilitate the analysis of the articles.

The following guidelines were established for formulating the scope by the methodological process: systematic bib-

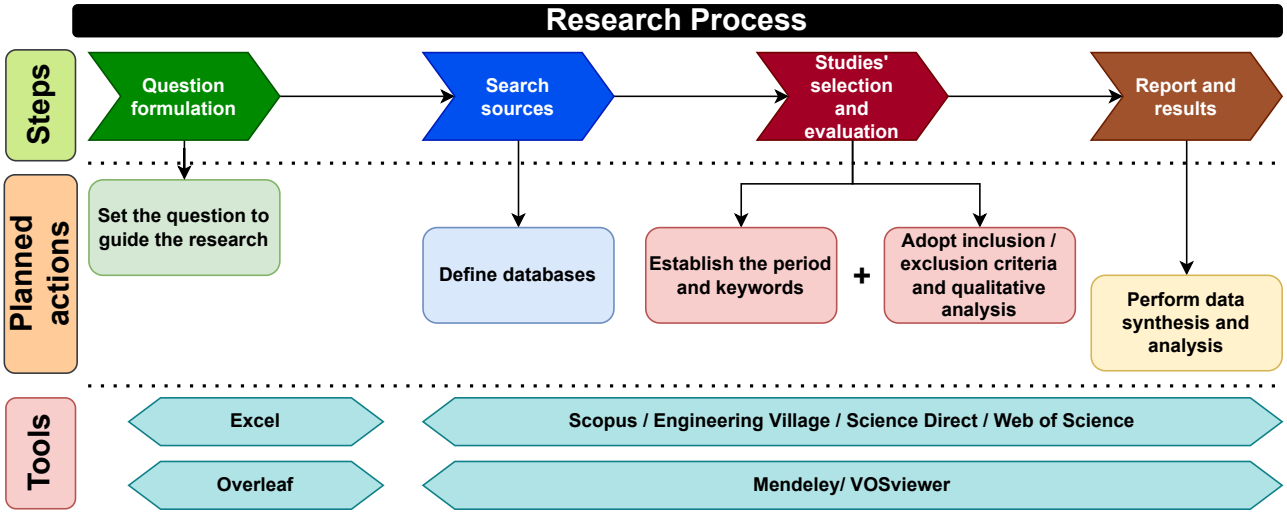

Figure 1. Research process (adapted from Khan *et al.*, 2003)

liometric research restricted to subject, title and abstract; use of Elsevier and Clarivate platforms.

The keywords, inclusion and exclusion criterias are exposed in Tab. 1.

Table 1. Keywords, inclusion and exclusion criterias

Keywords	Inclusion Criterias	Exclusion Criterias
(Gyrostabilized) AND (System OR Systems)	Journal articles / 2017 to 2023 / Language (English)	Other publications / Outside of the period defined / Other languages

The filtering and selection process followed the scheme shown in Fig. 2. Content analysis was performed to remove studies that contained non-gyrostabilized systems from the analysis. To be clear, many of them deal with the stability of some systems, but not all use a gyroscope or its effect to do such a task.

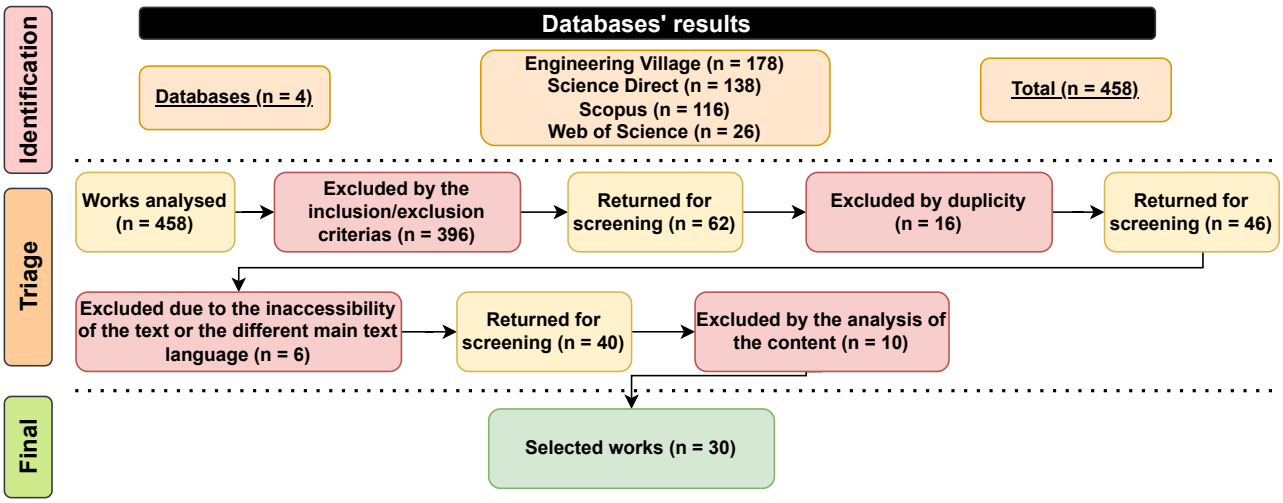

Figure 2. Filtering process

The searching resulted in 30 articles to be analyzed, listed in Tab. 2. To do that, they were imported to Mendeley Reference Manager and to VOSviewer. Figure 3 shows the graph produced in VOSviewer, containing the relationship between the keywords of these works.

From the study of articles' content listed in Tab. 2, the analysis and discussion about them are divided into the following topics: "Research focused on specific applications" and "Research focused on technological developments, control strategies and algorithms".

Table 2. Selected works

Author (Year)
Wu and Yang (2023) / Song *et al.* (2023) / Sorokin and Yaremenko (2022) / Fiot *et al.* (2022) / Chen *et al.* (2022) / Lukin and Krivosheev (2022) / Yang *et al.* (2022) / Peshekhonov *et al.* (2022) / Akinyele *et al.* (2021) / Tofigh *et al.* (2021) / Palraj and Rajamanickam (2021) / Lee *et al.* (2021) / Fuentes *et al.* (2021) / Shamolin and Krugova (2021) / Palraj and Rajamanickam (2020) / Neusypin and Selezneva (2020) / Unker and Cuvalci (2019) / Krobka (2019) / Pyrkin and Isidori (2019) / Wang *et al.* (2019) / Chelnokov (2019) / Awad *et al.* (2018) / Glumov *et al.* (2018) / Huang *et al.* (2018) / Pan *et al.* (2018) / Wu and Yue (2018) / Tsiruk (2018) / Testoyedov *et al.* (2017) / Luo *et al.* (2017) / Wu *et al.* (2017)

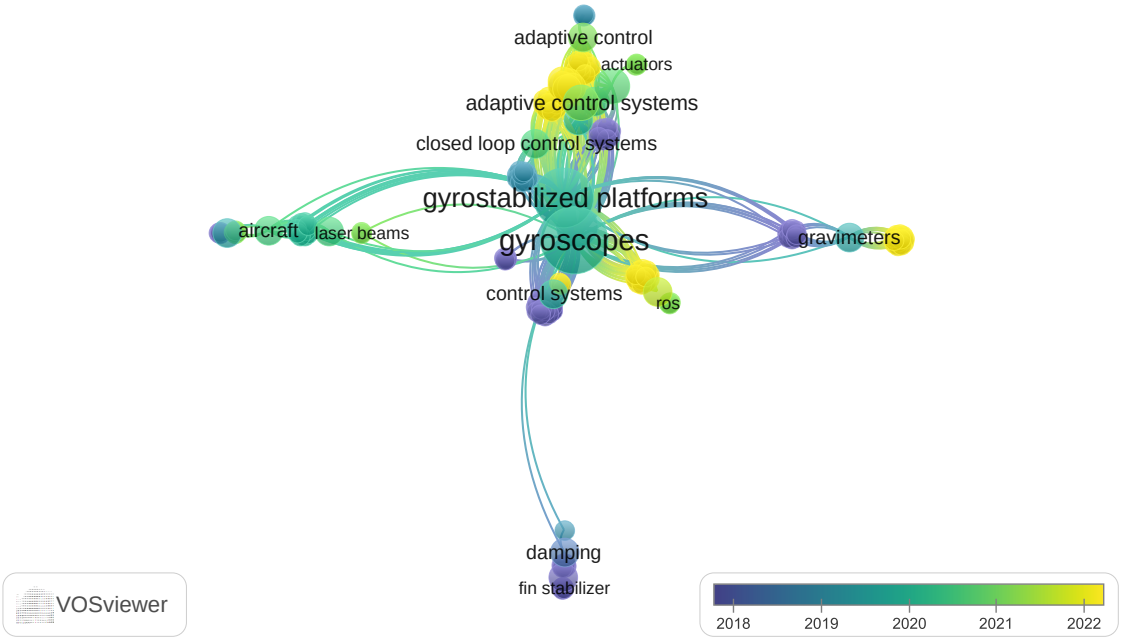

Figure 3. Relationship between the main keywords of the selected articles

3. RESEARCH FOCUSED ON SPECIFIC APPLICATIONS

This section is dedicated to studies aimed at specific applications. In order to better organize the analysis, the articles were segmented into the following applications: military and aerospace; marine and offshore; automotive and robotics; and structures.

3.1 Military and aerospace applications

One of the common applications of gyrostabilized systems is satellite control. In the work of Testoyedov *et al.* (2017), a brief history of the Russian space program is presented. The authors show the evolution that occurred in the orbit and attitude control systems (AOCSs), moving from passive control to active control. They also point out future challenges in this field of research, such as: deployment of large-scale antennas in space, in addition to their control and guidance; reduction of satellite payload mass; and use of electric propulsion in all phases of the spacecraft's mission. Finally, they state that the results achieved in the miniaturization of electronic sensors make it possible to create matrix receptors of an image in both the visible and the infrared radiation bands.

Glumov *et al.* (2018) focused on gyrostabilization problems for the angular position of large space structures (LSSs) in the process of their element-wise robotized assembly in orbit (as, for example, space radio telescopes and solar energy retransmitters). The authors proposed an approach to analyze the dinamic behaviour of these structures and to understand the unique characteristics and control challenges of this new type of space object, which can be modeled as a multi-frequency vibrating system with discrete development. Their paper highlights the need to adjust the basic control algorithm to account for the changing inertia properties of the structure during the assembly process. Furthermore, the authors demonstrate a feasible way to reduce the total mass of the structure by decreasing the rigidity of its construction elements, leading to reduced metal consumption. By presenting an extended control algorithm for powered gyrosta-

bilization, the paper ensures that the desired accuracy and control time are achieved, meeting the control performance requirements established for similar rigid objects. The algorithm is based on the Kalman filter and uses optimization techniques.

Chelnokov (2019) proposed new quaternion regular equations (RQEs) for optimal operation of space inertial navigation systems with an azimuthally stabilized platform and a gyrostabilized platform. In such equations, the total energy per unit mass of the spacecraft is used as an additional variable, rather than the Kleperian energy. Such an approach simplifies the differential energy equations included in the set of navigation equations. The author also discusses the construction of algorithms for the operation of inertial navigation systems using RQEs and their implementation in an onboard computer.

Neusypin and Selezneva (2020) studied astro-inertial systems (AINS) in their work. According to them, such systems are considered the most accurate among other navigation systems and consists of an astronomical navigation system installed on a gyrostabilized platform of inertial navigation system. When investigating the different sources of error, they conclude that the systematic drift of the gyroscopes is the main source of disturbance in the AINS, which impairs its accuracy. The authors propose a correction method based on an adaptive estimation algorithm, which is considered effective based on simulation results.

In Sorokin and Yaremenko (2022)'s work, the history of the development of the control moment gyroscope (CMG) is presented. The authors explain that the origin of the development of such devices came from marine stabilizers. However, when applying such devices in space technologies, new theories and solutions have emerged, since in most cases it is necessary to provide active triaxial control of the vehicle attitude instead of uniaxial stabilization. The engineering solutions for space applications are also very specific. Aspects such as minimum size, weight and energy consumed in conditions of zero gravity, vacuum and radiation are fundamental. The authors also point out the challenge of choosing the type of inertial actuator for the attitude control system of a spacecraft. Finally, they claim that a new class of gyroscope devices has been created: CMG for active three-axis control of spacecraft attitude.

Fiot *et al.* (2022) proposed a new method to estimate the attitude of an artillery shell in free flight. According to the authors, there is no need to have any ground-based position radar to do this. The method uses magnetometers and the pitch and yaw dynamic rotation frequencies generated by aerodynamic moments, which are directly visible in the accelerometer signals. The two sources of information are combined into an estimate of attitude by a specific nonlinear observer. The authors claim that the use of rate gyros in artillery shells is not adequate, as they are very fragile and would not withstand the stress of a shot. Also, spin rates generate induction effects, which strongly perturb magnetometers. In this sense, they exposes certain detrimental effects that impact the sensors and their solutions, such as: eddy current, misalignment and fictitious forces. In conclusion, the authors list some advantages of the developed method: the opening of new control perspectives for such symmetrical high-velocity projectiles and new trajectory estimates; speed estimation without the use of radars positioned on the ground, allowing the calibration of aerodynamic models of the shells by on-board data instead of wind tunnels. The experimental results demonstrated the feasibility of the method, which, in addition to using a minimal set of sensors, induces a computational load that is compatible with standard embedded processors.

3.2 Marine and offshore applications

Wu *et al.* (2017) addressed the problem with gravity measurements in deep oceans by designing an ultra-low-frequency platform leveling loop based on a mixed sensitivity H^{∞} approach. The objective was to obtain an overall measurement accuracy of 1 mGal. They applied it to a prototype, two-axis gyrostabilized platform marine gravimeter CHZ-II. Tests in the open sea resulted in reduction of pitch and roll off-level angles below 10 arc sec and 20 arc sec, respectively, even though in the presence of horizontal accelerations of a 50 Gal amplitude.

Luo *et al.* (2017) proposed an adaptative robust fin controller based on a feedforward neural network to reduce ship roll motion. The authors state that a conventional control scheme for fin stabilizers (as, for example, the Proportional-Integral-Derivative - PID - approach) is not feasible for all vessel types and all environment conditions. They present the various researches carried out so far aimed at the development of advanced control schemes, such as: H^{∞}, neural networks (NN), adaptive fuzzy logic scheme, linear quadratic regulator (LQR) combined with a disturbance observer, constrained model predictive control (MPC), adaptive robust sliding mode controller, L2-gain based adaptive fin controller and particle swarm optimization (PSO). However, according to the authors, the literature considered only one uncertainty parameter. They conclude by stating that environmental forces make it difficult to obtain a robust controller for reducing the ship's roll, as it is not easy to describe them mathematically. Numerical simulations show the validity and superiority of their control scheme compared to a proportional-derivative (PD) controller. However, the study was carried out with the 1 degree of freedom (DOF) model, suggesting the subsequent study in a model with 4 DOF for fin stabilization.

Awad *et al.* (2018) did a similar study on fin stabilizers. They proposed a control system based on neural networks (Direct inverse neural network control - DINNC) that takes into account roll response spectral transitions due to not only varying characteristics sea state but also changing sailing conditions. The networks were trained based on the wave spectrum defined by the Towing Tank Conference (ITTC), so that the controller response is the one to nullify the effect of disturbances. The results presented indicate a roll reduction of 50 to 65 % in two sea states. However, the authors explain that in the real case it is expected that the DINCC control scheme is sensitive to the behavior of disturbances and to the

dynamics of the complete model, affecting the performance of the controller. It is noted in this study the use of concepts associated with artificial neural networks (ANN), which are designed to simulate the process of the biological nervous system.

Huang *et al.* (2018) went one step further by proposing a control approach that stabilizes both the ship's roll and pitch. Such an approach is mainly based on predicting the ship's hydrodynamic forces, using two pairs of active fins. The controller is composed of three parts: a short-term predictor, a force estimator and a fin angle allocator. Simulations and experimental tests demonstrated that the controller acceptablely reduced pitch and roll movements simultaneously. The waves in various sea states were simulated on the basis of the ITTC wave spectrum, as the previous study.

Palraj and Rajamanickam (2020) conducted a study aimed at barge motion control using gyrostabilizers, in the context of offshore wind power generation. The study was done using the experimental generation of regular and irregular waves. Two small-scale barge models were built for the experiments: one with and the other without the static offshore wind turbine (OWT). The experiments were performed with the gyrostabilizer turned on and off, involving different speeds of the girostabilizer's flywheel. The results indicated the effectiveness of the gyrostabilizers in controlling the floater's movements, just sticking to the appropriate design of the device for each application.

Akinyele *et al.* (2021) did a study on the use of a gyroscope to improve the performance of an unmanned underwater vehicle navigated by a quadrant detector (QD) in shallow water docking operations under the influence of ocean disturbances. Three control schemes were used: forward Riccati and passive control, forward Riccati and proportional-derivative (PD) control, and forward Riccati and penalty function control. The authors conclude that such a device produces the intended effects and that the forward Riccati and penalty function control methods showed an acceptable performance. They warn that gyroscope properties must be carefully selected to match the condition of the vehicle and that, in practice, it is desirable for it to adapt to different sea conditions with irregular ocean disturbances. Therefore, they point to the robust adaptive control technique as a possible candidate to solve this problem. The authors also point out that there are uncertainties in the developed model, due to the linearization made in the proposal. Therefore, they suggest an active disturbance rejection observer to deal with this.

Lee *et al.* (2021) investigated the dynamical analysis and control synthesis for fractional-order pitch-roll system of marine vessels under regular waves in their work. To effectively regulate pitch-roll modes against extreme sea states, an adaptive fractional-order sliding mode control (AFOSMC) scheme has been employed. They used a modified 2 DOF marine vessel system to apply the AFOSMC and compared the proposed controller to a numerous design schemes. The authors also illustrated the pitch and roll resonance phenomena by using phase portraits and bifurcation techniques. The results from extensive simulation demonstrated its effectiveness. Although the authors used standard modes of pitch-roll movements, such movements could be detected by gyroscopes, which indicates the possibility of applying the study in gyrostabilized systems.

In a new study, Palraj and Rajamanickam (2021) focused on doing experiments with a barge mounted dynamic Offshore Wind Turbine (OWT) in order to reduce it's angular motions with OWT's rotor operating at different speeds. As in the previous study, the gyrostabilizer was used to perform this task. A scale model was build to do the experiments. To represent the floating OWT at the operational scenario, some rotor's speeds were selected: 60 rpm, 85 rpm and 114 rpm. The experiments were done with the gyrostabilizer "off" and "on" conditions. The results also demonstrated the efectiveness of using such a device to obtain the desired effect. However, the authors emphasize that it is very challenging to model a device with a large rotational mass and required levels of force to drive the gimbal to generate a stabilizing moment. Placing more than one gyrostabilizer in line or having one with more than one flywheel are options they suggest for future investigations.

Song *et al.* (2023) developed a control algorithm (angular rate feedback control - ARFC) based on the concept of tuned mass damping for an active gyrostabilizer. Such a device is composed of a gyroscope that measures the angular rate of the ship's roll movement, a controller that processes the proposed algorithm and an actuator connected to the precession axis. During the study, the authors found that the damping of the ship's roll motion can be increased by tuning the filter frequency of the control algorithm with the roll frequency. Numerical and experimental results demonstrated the viability of the proposal, including using relatively low-speed or light spinning wheels compared to passive gyrostabilisers. The set of devices for carrying out the experimental tests contained an MPU-6050, the Arduino UNO board and an NXP LPC 1768 microcontroller.

3.3 Automotive and robotics applications

Tofigh *et al.* (2021) presented in their work a new concept of gyrostabilizer which, according to them, can provide any desired roll moment. The proposal involves the use of a twin-flywheel arrangement. To validate the proposal, they derived the dynamic model of a bicycle together with the new gyrostabilizer using the Newton-Euler formulation. Next, they developed a robust non-integer sliding mode controller (fractional sliding mode controller - FSMC) to deal with roll disturbances. The simulations demonstrated that the innovative device proposed using the FSMC can control an autonomous two-wheeled vehicle, especially at low velocities. The result also demonstrated the superiority of the developed controller over other control strategies, such as: gain-scheduled integral state feedback with TSK-fuzzy switching

function and adaptive critical-based controller.

Fuentes *et al.* (2021) compared stabilization systems for mobile robots using internal and external stabilization strategies. The first strategy involved tilting and the gyroscopic effect, which are approaches that compensate for external forces (disturbances) that affect the system's stability. The model used for the analyzes was based on an articulated-arm-robot Mitsubishi RV-3AL mounted on a mobile platform SCITOS X3 by MetraLabs. Quantitative dynamic analysis was performed as follows: forces, torques, linear and angular displacements, velocities and accelerations were measured over time using the MSC.Adams/View software. Such values were sent as output signals to a closed control loop of the actuation system, modeled in MATLAB/Simulink. The obtained results show a great potential of application of the gyroscopic effect for the stabilization of mobile robots. Next, the authors compared two approaches to internal stabilization: direction of force and value of stability. For this, they used another robotic set, composed of the mobile robot platform SCITOS G5 and equipped with the robot arm Schunk LWA4D. An integration of different middlewares was used, so that the entire robot was controlled by the Robot Operating System (ROS) framework. The objective of this strategy was to detect the risk of the robot tipping over, an action that is not possible using any of the external stabilization strategy approaches. The results demonstrated that such approaches are promising for path planning algorithms.

Chen *et al.* (2022) studied a control scheme to balance a bicycle robot. A mathematical model was developed considering the addition of a reaction wheel and uncertainties. Next, a robust controller was designed, using integral terminal sliding mode (ITSM) and extreme-learning-machine (ELM). The function of the ELM is to be a compensator to estimate lumped uncertainties of the system. In the experimental studies, devices such as DC motors for the reaction wheel and the real wheels; a servo; a microcontroller unit (MCU) and a lithium battery were used. An encoder was used to capture reaction wheel speeds. To measure the roll angle, an MPU-6050 (Inertial Measurement Unit - IMU) was employed. Experiments were performed comparing the performance of a PID controller, boundary layer sliding mode (BLSM) and the proposed ITSM. The results indicate the superiority of ITSM, highlighting its great robustness, good tracking performance and reduced chattering.

3.4 Structures applications

Unker and Cuvalci (2019) highlighted in their study that performing active control in structural vibration problems is a more complex task compared to the commonly applied passive control. However, according to them, the gyrostabilizer can be considered as a passive control device, as it does not require any other external energy source. In addition, it allows the suppression of unwanted movements using its gyroscopic effect. In this context, the authors decided to study the use of a gyrostabilizer on a vertically cantilevered beam with a mass at the free end, mounted on a vibrating base. The focus of the study was to obtain optimized damping, stiffness and rotor speed values to minimize vibration responses. The study indicated that the beam tip response is influenced both by the rotation of the gyrostabilizer disk and by the optimal damping coefficient. Thus, such a relationship cannot be neglected, especially the minimum rotation at the resonance frequency.

4. RESEARCH FOCUSED ON TECHNOLOGICAL DEVELOPMENTS, CONTROL STRATEGIES AND ALGORITHMS

In this section, the articles were classified into two parts for a better analysis: technological advances and control strategies and algorithms.

4.1 Technological advances

Pan *et al.* (2018) designed and demonstrated the use of ultrasonic motors on a gyrostabilized platform with two degrees of freedom. According to the authors, electromagnetic motors (EMMs) are normally used on these platforms. However, requirements for gyrostabilized systems have evolved towards lighter, smaller components with greater precision. With that, the study of ultrasonic motors attracted several researchers. Its operation is based on the piezoelectric effect, which converts electrical energy into mechanical energy, generating friction between the rotor and stator, which results in the transfer of motion. Such devices have several advantages, such as: high position resolution, good power-to-weight ratio, good dynamic response and absence of electromagnetic interference. The authors used a PID controller for the system in question. To optimize their parameters, they considered several factors, such as: mechanical resonance, torque and moment of inertia coupling and non-linearities of the driver. Experimental tests and simulations were carried out and the results indicated that ultrasonic motors have a better performance in disturbance rejection under typical conditions.

Krobka (2019) presented a new gyroscopic principle, which may result in the development of a new generation of gyroscopes in cold atoms for space applications. According to the author, since 1985 the development of quantum-optical gyroscopes (ring laser gyro and fiber-optics gyro) has been carried out. Research on a new generation of inertial sensors in cold atoms was started by him in 2008. The author lists three main contributions of his work: a new kinematic principle of the gyroscope, which makes it possible to determine only the absolute angular velocity without limitations on the

measurement range; precise expressions of gyroscopic effects in cold atoms and de Broglie waves, based on kinematic and interferometric gyroscopic principles, which are fundamentally different from the Sagnac effect; and the asymmetry of the wave-particle duality seen in gyroscopy.

Shamolin and Krugova (2021) developed a diagnostic approach using a model of a gyrostabilized platform maintained on an aircraft, positioned in a specific location by a system of gyroscopes, which measure the oscillations of the aircraft. The approach involved the establishment of a monitoring problem, which, when solved, it is possible to diagnose the control channel of a platform in which a failure occurred.

Peshekhonov *et al.* (2022) analyzed the development of strapdown inertial airborne gravimetry (SAG). Such devices have certain advantages over gyrostabilized gravimeters, such as size, cost, power consumption, substantially expanding the research potential in gravity and allowing future applications in unmanned aerial vehicles (UAV). The authors cite the need to develop economically viable technical means based on the latest achievements in the field of strapdown and satellite navigation systems, electronics, informatics and computing. The errors of the gyroscopic sensors limit the accuracy in determining the horizontal component of the gravitational disturbance vector. Due to its relevance in applications involving geodesy, geology and high-precision navigation, many countries invest heavily in the development of SAG. The German company iMAR is the leader in the market for such devices, having models that meet the up-to-date requirements for measuring the gravity from the aircraft.

4.2 Control strategies and algorithms

Wu and Yue (2018) explain in their paper that the friction problem is a significant limiting factor in the controller performance of the three-axis electrical-optical gyro-stabilized platform (TEOGSP). In this way, they proposed a novel continuously differentiable nonlinear friction model, to result in a continuous control input, which is more suitable for further implementation. Next, they designed a desired compensation adaptive robust controller that uses the proposed friction model (DCARCF). To verify its performance, they compared with 4 other control schemes: adaptive robust controller (ARC); adaptive robust controller with static friction model (ARCF); desired compensation adaptive robust controller (DCARC); and PID. They concluded that the synthesized adaptive model compensation and regressor depends only on the desired trajectory and parameter estimates, which facilitates the process of tuning gains and alleviates noise measurement in the adaptive model compensation.

According to Tsiruk (2018), the currently existing stabilization systems for light armored vehicles (LAV) do not fulfill their task efficiently, and this fact is the cause of most losses in combat of the crew of armored vehicles. Then, the author studied the process of measuring mechanical quantities by modern instruments of stabilizers for weapons of LAV. The objective was to develop a stabilizer that uses small sensors and a system for vibration and shock impact. In this sense, the author sought to develop new equations to improve the accuracy of the stabilization systems and increase their speed. He concluded that the best model will be when the telescope is in a biaxial suspension with the vertical arrangement of the axis of the outer ring. He also derived analytical formulas for angular velocities and accelerations for further application in the digital block of stabilization system. Finally, he proposed methods of structural and parametric optimization to ensure the specified maximum possible stabilizer's accuracy.

Wang *et al.* (2019) focus their studies on solving problems of fast and accurate tracking of gyrostabilized platforms with unknown compound disturbances, unknown control directions and unknown hysteresis. Disturbances include two parts: friction torque and base motion. Their values are estimated using the radial basis function neural network (RBFNN). According to the author, the key point of applying the RBFNN is the transformation of the model, as it normalizes the disturbances. Through the construction of performance functions, the tracking errors of angle and angular velocity are constrained within prescribed boundaries. Such functions are defined under the structure of backstepping control. The authors then apply the Nussbaum function to solve the unknown direction of control problem, which appears in the last of backstepping control. According to the authors, the main contributions of their work are: approach considering the completely unknown hysteresis; prescribed output quality is guaranteed for gyrostabilized platforms through prescribed performance control; the proposed control approach is independent of accurate models. Therefore, its ability to reject disturbances is good and the computational cost is relatively low.

Pyrkin and Isidori (2019) addressed the problem of robust output regulation for multiple input - multiple output (MIMO) LTI systems with exogenous harmonic inputs and parameter uncertainties, especially those where measurements and controls do not have the same dimension. They discussed two stabilization approaches in the presence of plant uncertainties: one based on the extension of the mini-phase concept; and a new one based on the use of the H^{∞} and the linear matrix inequalities (LMI) methods. In both approaches, the aim is to show how adaptive tuning of the internal model can be implemented. Then, it is possible to obtain a controller that guarantees the asymptotic convergence of the regulated output to zero. The authors illustrate their approach by studying the motion control of a vessel.

Yang *et al.* (2022) proposed an error-driven adaptive feedback control with an extended state observer (ANCESO) for precise tracking of the three-axis electrical-optical gyro-stabilized platform (TEOGSP) in the presence of largely unknown matched and mismatched modeling uncertainties. They constructed an extended state observer (ESO) to provide estimates of both the unmeasurable velocity and the composite disturbances. A robust control law was used to suppress the residual

uncertainty. They compared the ANCESO performance with other two controllers: adaptive robust feedback controller with extended state observer (ARCESO), which did not have the parameter adaptation; and adaptive robust control (ARC), which is similar to ARCESO, but without friction compensation. The results indicated the effectiveness of the proposed scheme.

Lukin and Krivosheev (2022) defined three types of gyrostabilized platforms: power gyrostabilizer, indicator gyrostabilizer and indicator-power gyrostabilizer. The authors proposed an optimal design of an ad-hoc stabilization loop controller of a single axis gyrostabilized platform (SAGSP) of the first type. For this, they used a statistical approach, which aims to minimize the dispersion of the precession angle. The optimization problem was developed in Python computational language and applied to the SAGSP mathematical model. Two algorithms were used: differential evolution and simulated annealing. After simulations performed, the authors concluded that the presented method can be applied in other control systems that have disturbances of a harmonic nature.

Wu and Yang (2023) proposed a saturated adaptive robust feedback controller using an adaptive cascaded extended state observer (SAFCESO) for position control of three-axis electrical-optical gyrostabilized platform systems (TEOGSP). According to the authors, the main contributions of their work are: introduction of a smooth switching function to compromise between input saturation and the performance of the TEOGSP dynamic response, in addition to avoiding the singularity caused by the auxiliary system; the proposed controller can deal simultaneously with parameter uncertainties, matched disturbances and mismatched disturbances; velocity measurement for feedback is removed. Experimental comparisons were performed, considering controllers without the smooth switching function and general adaptive output feedback robust controller with disturbance compensation. The authors conclude that the unique cascade extended state observer (CESO) framework proposed to reduce noise amplification is practical to implement. The experimental studies confirmed the superiority of the proposed controller in terms of tracking accuracy, robustness, chattering and noise reduction. They suggest future studies in the area of TEOGSP control associated with impedance control and energy savings subject to performance trade-offs.

5. CONCLUSION

In the present work, a systematic bibliometric research was carried out in order to look for trends and limitations that still exist in gyrostabilized systems. Figure 4 shows the number of occurrences of the main keywords in the reviewed works, with some being grouped because they have the same meaning or a very close correlation.

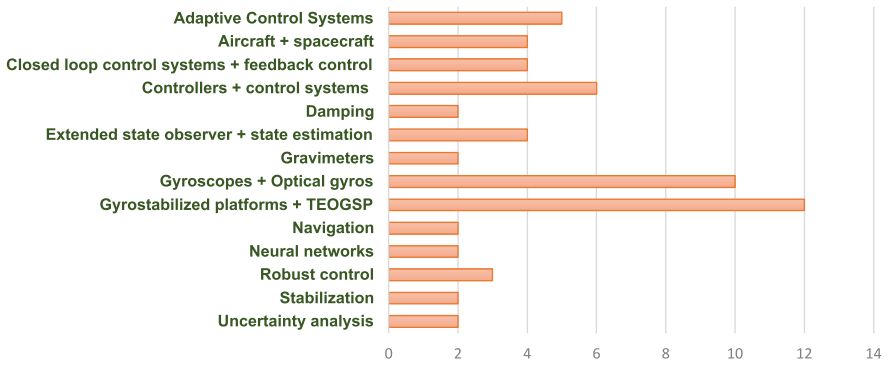

Figure 4. Summary of the main keywords of the papers and their number of occurrences

The conclusions obtained are the following:

- Kalman filters, optimization techniques, neural networks, machine-learning and/or robust control are present in some studies;
- due to the peculiar characteristics of space, gyrostabilized devices aimed at aerospace applications are being studied;
- the use of quaternions in spatial inertial navigation brings some advantages over the commonly used differential equations;
- there is a limitation in the use of gyroscopes in artillery shells, as they do not withstand the shock of firing and the spin rate causes interference in the magnetometers;
- it is possible to estimate the attitude of an artillery shell using accelerometers and magnetometers only. The computational load of the method is compatible with standard embedded processors;
- most of the researches has focused on marine and offshore applications;

- the stabilization of the ship's rolling motion is still a problem much investigated by researchers;
- the measurement of gravity in the deep ocean is a specific problem in the area of ocean engineering that requires greater accuracy. Therefore, there is a need to develop robust control algorithms as well as sensors and devices compatible with this requirement;
- the forces coming from the environment are still a challenge for the control of vessel roll movement, as it is not possible to describe them mathematically;
- studies on the control of active fins stabilizers are the most present in marine applications;
- prediction of the model or parameters by adaptive control is increasingly used;
- sliding mode control (SMC) is the most widely used robust control scheme in conjunction with other techniques that improve controller performance;
- some experiments used low-cost microcontrollers (example: Arduino) and Micro-Electro-Mechanical Systems (MEMS) inertial measurement units (IMU), which demonstrates the potential use of such devices in more complex applications;
- technological advances were made, such as the development of a new gyroscopic principle and the use of ultrasonic motors in gyrostabilized platforms;
- impedance control and energy savings subject to performance trade-offs are potential research topics in the area of control of gyrostabilized systems.

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