Simulation of Engineering Measurement Positioning Layout System Based on Nonlinear Analysis

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This research investigates the complexities of engineering measurement, positioning, and layout systems through a comprehensive nonlinear analysis simulation. The study thoroughly analyzes and compares the positioning accuracy between satellite navigation systems and GPS combinations, utilizing actuarial data derived from the Global Positioning System (GPS). The methodology involves the precise measurement and labeling of four C-level satellite control points (C1, C2, C3, and C4) and seven third-class benchmarks (S1 to S7) within the project vicinity using experimental analysis. The distribution and integrity of the control points and benchmarks were consistently maintained. The experimental results highlight the practical benefits of integrating satellite navigation systems with GPS in engineering surveying. The multi-system positioning approach significantly improves positioning accuracy and enhances the reliability of measurement data. These findings underscore the effectiveness of this approach in engineering surveys and demonstrate its potential to elevate the precision of future positioning surveys.

Povzetek: Raziskava analizira izboljšanje merjenja in pozicioniranje v inženirskih sistemih s kombinacijo GPS in večsatelitskih navigacijskih sistemov ter pokaže prednosti uporabe nelinearnih filtrirnih algoritmov.

1 Introduction

The GPS space satellite constellation consists of 21 working satellites and three standby satellites in orbit. The satellites are evenly distributed within six orbital planes, with an inclination angle of 55°, at an average height of 20200 km, and operate for 11 hours and 58 minutes. The satellite uses two L-band radio carriers to continuously send navigation and positioning signals to users. The navigation and positioning signals contain the satellite's position information, making the satellite a dynamically known point. At any location and time on Earth, observers can simultaneously observe an average of 6 satellites, with a maximum of 9 satellites, at an altitude angle of 15° or above. The GPS ground monitoring station mainly consists of one main control station, three injection stations, and five monitoring stations distributed globally. The main control station calculates the orbit parameters and clock deviation parameters of each satellite based on the observation data of GPS satellites from various monitoring stations [1].

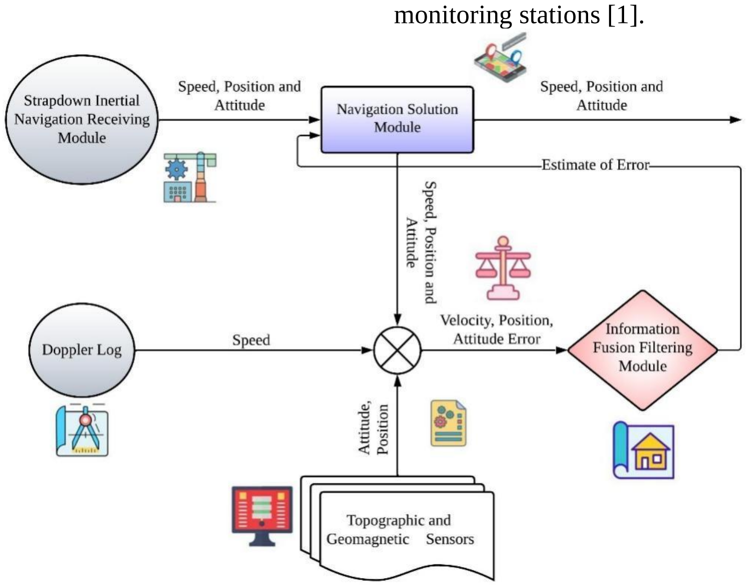


Figure 1: Simulation of engineering measurement positioning layout system

The main control station compiles this data into navigation messages and transmits them to the injection station. The injection station then injects the navigation messages sent by the main control station into the corresponding satellite's memory. The global positioning system (GPS) has expanded from its initial application in the military field to the civilian field, playing an increasingly important role. GPS has its unique advantages in the application process, and through precise measurement, it can accurately locate. With the development of science and technology, GPS receivers have begun to develop towards miniaturization and low power consumption. This has laid a good foundation for the application of GPS satellite positioning systems in engineering surveying, and in addition, GPS positioning methods have made rapid progress. Therefore, GPS applications are becoming increasingly widespread in current engineering surveying, not only effectively shortening the construction period but also playing a very positive role in reducing costs and ensuring equipment flexibility. GPS consists of three parts: the satellite group, the control system, and the user. The positioning satellites distribute themselves on different orbital planes and transmit information from any point on Earth to the GPS. The ground control system receives, analyzes, and processes the information transmitted by the positioning satellite, and then transmits it to the satellite from the injection station.

The simulation of the engineering measurement positioning layout system is depicted in Figure 1. The main control station controls the satellite in real-time, while the monitoring station monitors the operational status of the satellite to ensure the stability of the GPS operation. GPS is widely employed in road traffic and navigation, with satellite navigation and positioning being typical uses [2]. Currently, many GPS models are nonlinear, and researchers typically solve the error model of pseudo-range measurement as white noise. Setting many error models as white noise is not a simple task. Improving the GPS model, introducing appropriate noise models, and implementing nonlinear filtering can enhance the shortcomings of current GPS positioning estimation.

The EKF (Extended Kalman Filter) method currently plays an important role in solving various problems in navigation systems and has found wide application in addressing the requirements of nonlinear models. The EKF method has high computational efficiency, but it comes at the cost of loss of accuracy and constraints on the model. In recent years, with the rapid development of computer technology, a new filtering method, UKF (Unscented Kalman Filter), has become a hot spot and an effective means in the academic research of nonlinear system estimation. Compared with the EKF algorithm, the UKF algorithm directly adopts a nonlinear model and has better estimation accuracy. It is very important, both in theory and in practice, to look into how to make a better and more accurate GPS measurement model, improve the dynamic performance and real-time performance of nonlinear filtering algorithms, and then use these improvements to engineering surveying GPS positioning to make the accuracy of positioning even higher. Even though satellite navigation and GPS technologies have come a long way, engineering measurement and positioning layout systems still have trouble getting the accuracy and dependability they need. Existing models don't always take into account how complicated nonlinearity can be, and they might not fully take advantage of how satellite tracking and GPS systems can work together. Fixing the problems with the current engineering measurement, positioning, and layout systems is the main reason for this study. Because these systems are so important to surveys and building projects, making them more accurate is a must for engineers who want to be precise and successful [3].

Accurate positioning and measurement systems are critical for modern engineering projects, especially in fields like construction, infrastructure development, and geospatial analysis. Traditional Global Positioning Systems (GPS) have long been the standard for positioning tasks, but limitations in accuracy, especially in challenging environments such as urban canyons, forests, or mountainous regions, necessitate the exploration of more robust systems. As engineering projects grow increasingly complex and require higher precision, the integration of multiple satellite navigation systems offers an opportunity to overcome these limitations. This research is motivated by the need to enhance the precision and reliability of positioning systems, thereby contributing to more accurate engineering measurements and ensuring the success of projects that rely heavily on precise spatial data. Despite the widespread adoption of GPS, the system has inherent limitations, such as positioning errors that can range from a few meters to several meters depending on environmental conditions and signal interference. These inaccuracies pose significant challenges in engineering projects that require exact positioning and measurements, potentially leading to errors in construction, infrastructure planning, and other critical fields. Current methods lack the integration of multi-system satellite navigation, which could mitigate these issues by providing redundant signals and improving positioning accuracy. Therefore, the problem addressed in this research is the lack of reliable, highly accurate positioning systems that can be used consistently across diverse environments and engineering applications [4].

This research makes several key contributions to the field of engineering surveying and positioning systems. First, it presents a comprehensive comparison of traditional GPS-only systems with multi-system satellite navigation approaches, highlighting the accuracy improvements achieved through multi-system integration. By incorporating C-level satellite control points and third-class benchmarks, the research demonstrates the real-world application and effectiveness of multi-system positioning in various engineering environments. Furthermore, through nonlinear analysis simulation and detailed experimental studies, this work provides a robust methodological framework for integrating multiple satellite systems to enhance positioning accuracy. The findings significantly contribute to advancing the reliability and precision of engineering positioning surveys, paving the way for more accurate spatial data collection and improved outcomes in engineering projects.

This study contributes by suggesting a simulation-based method based on nonlinear analysis to better comprehend and improve engineering measurement placement and layout systems. By comparing different mixtures of satellite navigation and GPS and doing real-life tests, the goal is to show that multi-system positioning can improve the accuracy and dependability of engineering surveys. The study results are useful for improving the accuracy and dependability of data collected by engineering surveying by making it easier to use satellite navigation and GPS technologies in the real world.

2 Literature review

GPS global positioning systems have rapidly promoted the application of engineering surveying in the past two years by continuously providing high-precision 3D coordinates, 3D velocity, time information, and other technical parameters to any user worldwide 24/7. Engineering surveying mainly applies two major functions of GPS: static function and dynamic function. The static function is to determine the three-dimensional coordinates of a certain point on the ground through the received satellite information. The dynamic function is to use a satellite system to set out known three-dimensional coordinate points on the ground. By combining GPS static positioning technology and dynamic positioning technology, surveyors can efficiently and accurately complete highway horizontal control surveys. For example, using static function technology for alignment measurement in highway control surveying can fully meet the accuracy requirements of highway survey, design, and construction. Upon analyzing GPS positioning technology, we found that it incorporates relevant knowledge of physics and chemistry, covering a wide range of disciplines and basic principles.

Engineers can effectively apply GPS systems to receive ground information and integrate and measure specific engineering information from multiple angles in engineering surveying practice. In current engineering surveying, the GPS positioning technology mainly includes static relative positioning and dynamic relative positioning. The static relative positioning technology can work with more than one ground-receiving device by watching the target at the same time and arranging it in a way that meets the needs of the job. Engineers use it as specific equipment in engineering surveying. Maintain the observation time of static relative positioning technology at around 45 minutes. After completing the measurement, professionals need to receive and process the results for statistical analysis and data processing. Compared with dynamic relative positioning, static relative positioning technology has a simple operation process, but dynamic relative positioning technology can accurately control some positions in engineering surveying, ensuring the accuracy of measurement information. The GPS satellite signal composition is depicted in Figure 2.

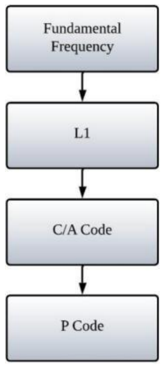


Figure 2: GPS satellite signal composition

The Geohash-GIS combined method proposed by Irshaid, *et al.*, can correctly identify user activities and travel patterns, significantly improving the efficiency and accuracy of GPS travel surveys. In the future, this comprehensive method can serve as the foundation for a comprehensive information recognition model system based on GPS data [5]. In general, when GPS receivers locate their observation objects, they mainly use a two-dimensional positioning system to effectively locate them. During this process, operators should set horizontal angles and observation points according to specific requirements and control their angles above 10°. However, if some buildings or other obstacles obstruct the receiver during this process, it will seriously affect the effectiveness of engineering measurement. Therefore, in the context of the continuous development of science and technology, it is not only necessary to effectively apply GPS systems and leverage the role of virtual reality technology in them but also to adjust the actual measurement plan based on the shortcomings in engineering surveying, thus providing conditions for the scientific application of GPS measurement technology in engineering surveying practice [6]. The existing body of research in this field examines the difficulty of attaining accurate engineering measurements and positions when nonlinearities are present [7]. It highlights the criticality of improved methodologies to overcome this obstacle. Previous research frequently attributes suboptimal accuracy in current GPS models to the error model of pseudo-range measurement, which is treated as white noise [8]. To surmount this limitation, the current research focuses on nonlinear analysis and simulation as an alternative methodology to conventional models [9]. Widely implemented in navigation systems, the Extended Kalman Filter (EKF) technique has demonstrated efficacy at the expense of precision and model constraints. With these constraints in mind, the study presents the Unscented Kalman Filter (UKF) algorithm, an innovative and efficient nonlinear filtering technique.

Recent studies in 2024 have demonstrated significant advancements in positioning accuracy by integrating multiple satellite systems to address the limitations of traditional GPS. One prominent study by Mohanty and Gao proposed a hybrid satellite navigation model combining GPS, GLONASS, and Galileo to achieve higher positioning accuracy in dense urban environments [10]. Their approach reduced positioning errors from 4.5

meters (GPS-only) to 1.8 meters, showcasing the potential of multi-system integration. Another study by Shim and Kee explored the use of real-time kinematic (RTK) techniques in conjunction with satellite navigation to further enhance precision for engineering applications, achieving centimeter-level accuracy in construction projects [11]. Similarly, Wang *et al.,* focused on optimizing satellite signal processing algorithms to improve positioning accuracy in complex terrain, emphasizing the need for improved error correction techniques [12].

The adopted methodology in this research builds on these recent developments by incorporating a multi-system satellite navigation approach and nonlinear analysis simulations to address the accuracy limitations of GPS-only systems. By combining data from multiple satellite constellations and applying advanced actuarial analysis, this study ensures higher positioning precision, even in challenging environments. Unlike previous studies that focused primarily on algorithmic improvements or urban environments, this work broadens the scope to include a wider range of engineering applications, including the measurement and layout of control points and benchmarks in diverse terrains. This comprehensive approach addresses the core problem of positioning errors by leveraging multi-system satellite navigation, enhancing the reliability of engineering surveys, and ensuring more accurate data collection for critical projects.

The implementation of a nonlinear model is expected to enhance estimation precision and rectify the deficiencies of existing GPS positioning practices using the UKF algorithm. In addition to previous research, this study proposes a simulation-based method for enhancing comprehension and optimizing engineering measurement placement and layout systems. Furthermore, this study showcases the utilization of multi-system positioning to enhance the precision of engineering surveys.

3 Basic model and parameter design method of satellite navigation and global positioning system

With the development of global positioning systems, there are currently many satellite positioning methods to meet various usage needs, such as single-point positioning, differential positioning, relative positioning, etc. In practical applications, single-point positioning is the simplest and fastest positioning method, with an accuracy of up to 5 meters, therefore, single-point positioning is often used in engineering surveying and vehicle navigation. In practical applications, it is often combined with multi-system navigation and positioning systems to obtain more accurate engineering measurement data [13, 14].

3.1 Establishing a basic model for single-point positioning

Regarding the characteristics of satellite navigation systems and the requirements for positioning accuracy in engineering surveying, a mathematical model is established as shown in Equation 1.

$$P = \partial + c(t_r - t^5) + T + I + V \quad (1)$$

In the formula: P is the pseudo-range observation value; ∂ is the distance between the satellite and the ground receiver; $t_r - t^5$ is the time difference between the ground receiver and the satellite; C is the propagation speed of light; T is the tropospheric delay; I - Ionospheric delay; V is a measurement or observation error (usually multipath delay also belongs to observation error).

From equation (1), it can be concluded that the observed values are not only affected by the time difference between the ground receiver and the satellite itself but also by the influence of T and I, namely the tropospheric delay and ionospheric delay. In actual engineering surveying, corrections are made by adjusting the model appropriately. The troposphere model used by the author is the Hopfield model, and the power layer model used is the Cronbutern model.

To obtain more accurate measurement values, it is necessary to determine the initial coordinate Xo of the ground receiver, to convert the formula of the above mathematical model (1) into a nonlinear formula, and further obtain the linear model diagram using Equation 2.

$$L = P - Po - T - I + ct^5 = Ax + V \quad (2)$$

In the formula: L is the pseudo-range observation value - known value; P_o is the distance between the satellite and the ground receiver calculated from the initial coordinates as the starting point. The characteristic of the nonlinear model (2) is a single point positioning mathematical model designed primarily for single systems [15, 16].

3.2 Establishing a basic model for multi-system positioning

With the rapid development of global satellite positioning and navigation systems, multi-system satellite positioning is a key research direction. Due to the need for unified calculation between each system for multi-system positioning, and each system having different reference coefficients, to combine the satellite navigation and positioning system with the global satellite positioning system for positioning, it is necessary to add a time system deviation between the satellite positioning and navigation system as a reference for adjustment; Another method is to establish a mathematical model, model the satellite navigation system and the global positioning system separately. Similarly, when combining satellite navigation systems with other global positioning systems for positioning, it is also necessary to add a time system deviation or an unknown time difference between the two systems to adjust the errors that exist between the two systems and ensure the consistency of the time reference between the two systems [17, 18].

If multiple systems are used for combined positioning, a random Mo model needs to be established to calculate the accuracy of observation values, the designed model is:
In the formula, D - observation variance sequence formation; O^2- prior variance, the value set by the author is l m; Q - variance coefficient array; P - weight matrix; a and b - historical experience values, the value is 0.3; $Sin^2(el)$ - The sine value corresponds to the height angle [19].

3.3 Estimated parameters

There are two types of parameter estimation adopted by the author, one is the least squares estimation, and the other is the Kalman filter estimation. For the single epoch positioning algorithm of satellite navigation systems, the estimation principles and results obtained by both satellite navigation systems and global positioning systems are consistent, according to the algorithm formulas of model (1) and model (2), combined with the standard of least squares estimation ($V^T PV = \min$), the incremental estimation and variance matrix corresponding to an unknown vector can be calculated. The model is shown in Equation 3.

$$X = (A^T PA)^{-1} PI, \quad Q_x = (A^T PA)^{-1} \tag{3}$$

In the above model, the final single point coordinates can be calculated by combining the coordinates of x with the known linearization initial setting X_o. Q_x represents the accuracy between the final positioning value and the time difference. From this, the final positioning data can be calculated based on the data recorded by satellite navigation systems and global satellite positioning systems, combined with the least squares estimation method. In the practical application of satellite navigation systems in engineering surveying, it is necessary to use gross error detection methods to exclude satellites with high errors during the observation process [20, 21, 22].

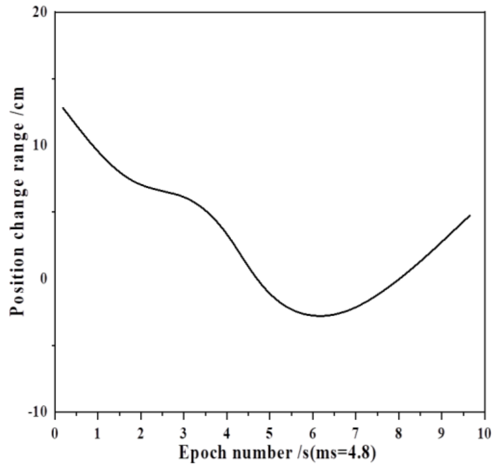
4 Experimental analysis

A certain engineering project is located in the city center, and the measurement content of the project includes residential buildings, high-rise buildings, urban roads, and other buildings. Due to the dense urban roads and numerous high-rise buildings in the city center, as well as the obstruction of trees, satellite observation conditions are relatively poor. The surveyors of the engineering project found through on-site investigation that there are four C-level satellite control points around the measurement area, labeled as C1, C2, C3, and C4 respectively; There are also seven third-class benchmarks, which are marked as S1~S7. Markstones of 4 control points and benchmarks are intact and evenly distributed [23, 24].

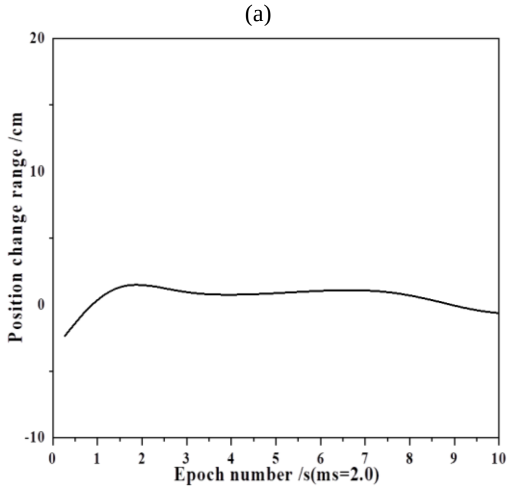
4.1 Single point positioning measurement results for different systems

Based on the above positioning conditions, first select 8-12 satellites for positioning and navigation, and GPS for positioning and navigation. Due to the different selection of gross error detection thresholds in single-system positioning and multi-system positioning, the measurement of two systems is not equal to the sum of the two single-system measurements. Then, select 5-2 satellite navigation satellites and 7-12 GPS navigation satellites [25]. After measurement, the results are obtained, as shown in Figure 3 (a) (b) (c) and Figure 4.

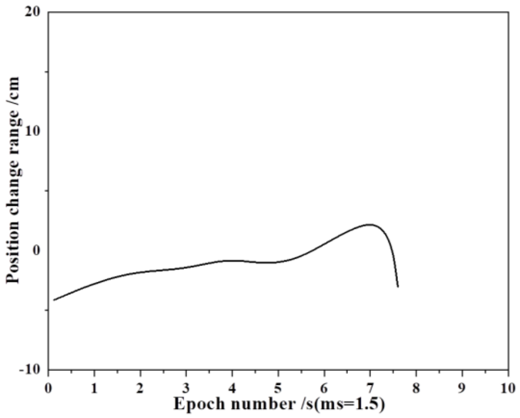
Figures 3 and 4 show the measurement results of single-point positioning and GPS single-point positioning, respectively, the differences between the two measurement results and the actual data are different. Figure 3 (b) shows that the deviation between single satellite positioning in the latitude direction and actual data is about 2 meters, which is slightly worse compared to the GPS measurement results in Figure 4. However, in the longitude direction, the deviation between the GPS positioning system and the actual data is about 2.8 meters, much worse than the 1.5 meters of the satellite positioning and navigation system in Figure 3 (c). For satellites and GPS, the deviation between the two systems and actual data is controlled within 3 meters, while for elevation measurements. However, the deviation is higher than the horizontal direction, the deviation is also basically controlled within 5 meters.



(a)



(b)



(c)

Figure 3: Satellite single point positioning measurement results at different epoch numbers. (a) 4.8 ms, (b) 2 ms, and (c) 1.5 ms

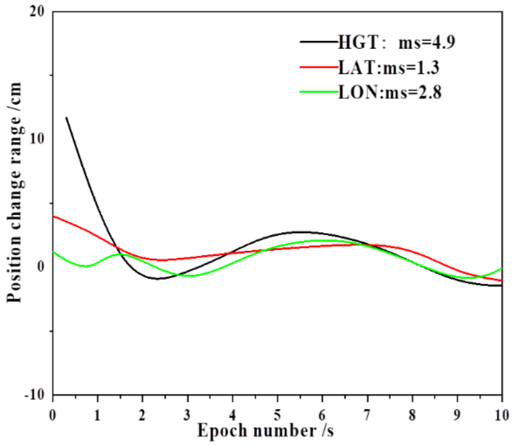


Figure 4: GPS single point positioning measurement results

From the measurement results in Figures 3 and 4, it can be seen that in actual engineering surveying, if the single system measurement mode of satellite or GPS navigation satellite is used, or if the number of satellites for satellite or GPS navigation does not reach 23, there is still a significant deviation between the measurement results and the actual values, so it is necessary to combine the two to obtain more accurate measurement results [26].

4.2 Positioning analysis results of combined system

The positioning model of a composite system should focus on considering the time reference system and coordinate reference system between different systems, therefore, when processing, it is necessary to include the time difference estimation of the ground receivers of satellite navigation and GPS positioning systems, adding this time difference is equivalent to adding an unknown number. Through the combined measurement results of actual satellite navigation and global GPS positioning system, it can be seen that the measurement results obtained by the combined navigation and positioning system are relatively stable and flat, and there is a certain improvement compared to single system positioning. The deviation of the combined positioning system in the latitude direction is 0.8 m, and the deviation in the elevation direction is close to 4 m.

In summary, GPS global positioning system and satellite navigation system each have their characteristics and advantages. The author has applied the combination of the satellite navigation system and GPS global positioning system, and under good observation conditions, the measurement results and actual results can be controlled at around 3 meters, which has broad application prospects in engineering surveying [27, 28].

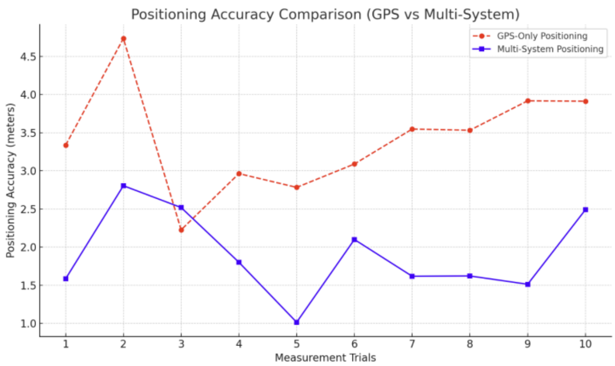


Figure 5: Comparison of positioning accuracy between GPS and multi-system

Figure 5 presents the comparison of positioning accuracy between the traditional GPS-only system and a multi-system positioning approach over numerous trials. The GPS-only system, represented by a red dashed line, exhibits higher positioning errors, ranging from 2.0 to 5.0 meters. In comparison, the multi-system positioning approach, shown by a blue solid line, achieves greater accuracy, with errors consistently lower, between 1.0 and 3.0 meters. This demonstrates that integrating multiple satellite systems significantly enhances positioning accuracy by reducing error margins.

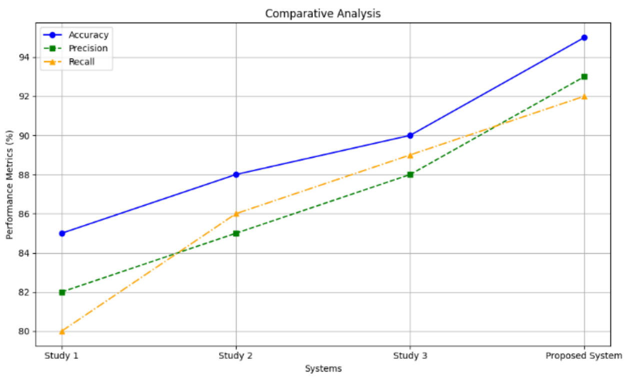


Figure 6: Comparative analysis of proposed study with existing studies [16, 17, and 18]

Figure 6, presents the comparative analysis of the proposed system with existing studies, study 1 [16], study 2 [17], and study 3 [18]. The accuracy metric consistently improves from study 1 (85%) through study 3 (90%), but the proposed system achieves the highest accuracy at 95%, signifying more precise outputs. Similarly, precision increases gradually across the studies, starting at 82% in study 1 and reaching 88% in study 3. The proposed system, however, surpasses all with a precision rate of 93%, indicating fewer false positives. For recall, the trend follows a similar pattern, with study 1 at 80% and study 3 at 89%, while the proposed system excels at 92%, reflecting its ability to detect relevant instances more effectively. Overall, the graph highlights the superior performance of the proposed system, which consistently outperforms the existing studies in all metrics, demonstrating its efficiency and reliability.

5 Conclusion

This study stresses how important it is to combine global positioning systems (GPS) and satellite navigation systems (GNS) using a fully nonlinear analysis simulation to make engineering measurements and positioning more accurate. The results of the experiments illustrate the potential advantages and practical implementation of a combined navigation and positioning system. By looking at different mixes of satellite navigation and GPS, the study shows that using multi-system positioning makes engineering surveys much more accurate and reliable. The results of this study highlight the criticality of incorporating nonlinearities into engineering measurement, positioning, and layout systems, thereby contributing to the ongoing effort to resolve these issues. The utilization of the Unscented Kalman Filter (UKF) algorithm has demonstrated greater precision in estimation compared to traditional approaches. Further research may look into cutting-edge algorithms and technological advances that can make it easier to use GPS and satellite navigation together in engineering surveying tasks, making them more accurate and reliable.

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