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Auto Storage System

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Abstract*: In the modern era of logistics and supply chain management, efficient storage solutions are paramount for maximizing space utilization, reducing human error, and enhancing retrieval speed. This paper presents an innovative Automated Storage System (ASS) designed to revolutionize warehousing operations. The proposed system integrates cutting-edge technologies such as robotics, artificial intelligence (AI), and the Internet of Things (IoT) to create a highly efficient, scalable, and intelligent storage solution. The Automated Storage System leverages robotic shuttles and conveyors for precise and rapid handling of goods, ensuring seamless inventory management. The AI algorithms optimize storage locations and retrieval paths, significantly reducing the time and energy required for operations. IoT sensors provide real-time monitoring and data collection, enabling predictive maintenance and minimizing downtime. Key features of the ASS include space optimization through advanced algorithms for dynamic storage allocation, maximizing space usage; high-speed robotic shuttles capable of handling multiple items simultaneously for increased speed and efficiency; a modular design allowing easy expansion as business needs grow; IoT integration for continuous monitoring of inventory levels and system performance; and energy-efficient components and smart power management systems.*

This system not only enhances operational efficiency but also ensures high accuracy in inventory management, thereby reducing losses due to errors and improving overall productivity. The implementation of the Automated Storage System marks a significant advancement in warehouse automation, setting a new benchmark for future developments in the field. The paper discusses the design, implementation, and benefits of the Automated Storage System, supported by case studies and performance metrics from pilot projects. The results demonstrate substantial improvements in storage efficiency, operational speed, and cost savings, making the ASS an essential innovation for contemporary warehousing solutions.

Keywords: supply chain management

I. INTRODUCTION

In the dynamic landscape of logistics and supply chain management, the demand for innovative storage solutions has never been greater. As businesses strive to optimize their operations, the need for efficient, accurate, and scalable warehousing systems becomes critical. Traditional storage methods, often labor-intensive and prone to errors, can no longer keep pace with the growing complexity and volume of inventory management. To address these challenges, this paper introduces an Automated Storage System (ASS), a state-of-the-art solution designed to transform warehousing operations through the integration of advanced technologies such as robotics, artificial intelligence (AI), and the Internet of Things (IoT).

The Automated Storage System represents a paradigm shift in how goods are stored, managed, and retrieved. By employing robotic shuttles and conveyors, the system ensures precise and rapid handling of items, drastically improving inventory accuracy and operational efficiency. AI algorithms play a pivotal role in optimizing storage locations and retrieval paths, thereby minimizing the time and energy expended on these tasks. Additionally, IoT sensors provide real-time data on inventory levels and system performance, enabling predictive maintenance and reducing unexpected downtime.

Key features of the ASS include dynamic storage allocation for optimal space utilization, high-speed robotic shuttles for enhanced operational speed, a modular design that allows for seamless scalability, and energy-efficient components for sustainable operations. These features collectively contribute to a system that not only meets the current demands of warehousing but also sets a new standard for future developments in the industry.

This paper will delve into the design and implementation of the Automated Storage System, highlighting its benefits through case studies and performance metrics from pilot projects. The findings demonstrate significant improvements in storage efficiency, speed, and cost-effectiveness, underscoring the ASS as a crucial innovation for modern warehousing solutions.

1.1 Necessity

The necessity for an Automated Storage System (ASS) in contemporary warehousing and logistics operations is driven by several critical factors that traditional storage methods increasingly fail to address. As global commerce continues to expand, businesses face mounting pressures to optimize their supply chain processes to remain competitive. This section elucidates the key reasons why an automated storage solution is indispensable in the modern context.

Increasing Inventory Complexity and Volume With the rise of e-commerce and global distribution networks, the volume and complexity of inventories have surged. Traditional manual storage and retrieval methods are often inadequate for managing the sheer scale and diversity of items, leading to inefficiencies and higher error rates. An automated system can handle large volumes of diverse products with precision and speed, ensuring accurate inventory management.

- Need for Operational Efficiency: Efficiency in warehousing operations translates directly to cost savings and faster fulfillment times. Manual processes are labor-intensive and time-consuming, often resulting in bottlenecks and delays. Automated Storage Systems streamline these operations by using robotics and AI to expedite the storage and retrieval processes, significantly reducing labor costs and increasing throughput.
- Space Optimization: Space is a premium resource in warehousing. Traditional storage systems often fail to maximize space utilization, leading to wasted capacity. Automated systems employ advanced algorithms for dynamic storage allocation, ensuring optimal use of available space. This is particularly crucial in urban areas where real estate costs are high.
- Reducing Human Error: Human error is a significant contributor to inventory discrepancies and losses. Manual handling of goods can lead to mistakes in counting, misplaced items, and data entry errors. Automation minimizes these risks by ensuring consistent and accurate operations, thereby improving overall inventory accuracy and reducing loss.
- Real-Time Inventory Monitoring: In today's fast-paced business environment, real-time data is vital for effective decision-making. Traditional systems often lack the capability to provide instant updates on inventory levels and system performance. Automated Storage Systems, integrated with IoT sensors, offer continuous monitoring and real-time data collection, enabling better inventory management and predictive maintenance.
- Scalability and Flexibility: Business needs are constantly evolving, and scalability is essential for accommodating growth. Manual systems can be inflexible and difficult to scale without significant investment and disruption. Automated systems, with their modular design, allow for easy expansion and adaptation to changing business requirements, providing a future-proof solution.
- Labor Shortages and Safety: Labor shortages in the warehousing industry are becoming increasingly common, exacerbated by the physically demanding nature of the work. Automation addresses this issue by reducing dependency on manual labor. Additionally, automated systems enhance workplace safety by minimizing the need for human workers to perform hazardous tasks, thereby reducing the incidence of workplace injuries.In summary, the necessity for an Automated Storage System arises from the need to handle increasing inventory complexity and volume, achieve operational efficiency, optimize space, reduce human error, provide real-time monitoring, ensure scalability, and address labor shortages and safety concerns. The implementation of such a system is not just a technological advancement but a strategic imperative for businesses aiming to stay competitive in the modern marke

1.2 Objective

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The primary objective of the Automated Storage System (ASS) is to revolutionize warehousing operations by integrating advanced technologies to enhance efficiency, accuracy, and scalability. This involves several specific goals. Firstly, the system aims to optimize space utilization through dynamic allocation algorithms that maximize storage capacity and accommodate higher inventory volumes within the same physical footprint. Enhancing operational efficiency is another key goal, achieved by streamlining storage and retrieval processes using high-speed robotic shuttles and conveyors, which significantly increase throughput and reduce labor costs. Improving inventory accuracy by minimizing human error in inventory management is also crucial, ensuring up-to-date and precise inventory counts. Additionally, the ASS integrates IoT sensors for real-time monitoring and data collection, supporting real-time decision-making and predictive maintenance. Scalability and flexibility are built into the system's modular architecture, allowing for easy expansion and adaptation to changing business needs. Energy efficiency is enhanced through the use of energy-efficient components and smart power management, reducing operational costs and environmental impact. The system also aims to improve safety and reduce labor dependency by automating hazardous or physically demanding tasks, thus creating a safer work environment and addressing labor shortages. Providing a future-proof solution is essential, ensuring the system remains competitive and viable by continuously integrating emerging technologies. Achieving cost savings through increased efficiency, lower labor requirements, and minimized errors is a fundamental goal, ultimately offering a significant return on investment. Lastly, the ASS.

II. LITERATURE SURVEY

2.1 Description

The Automated Storage System (ASS) is an advanced warehousing solution designed to enhance efficiency, accuracy, and scalability in storage and retrieval operations. This system incorporates state-of-the-art technologies, including robotics, artificial intelligence (AI), and the Internet of Things (IoT), to create a highly efficient and intelligent storage environment.

At the core of the ASS are robotic shuttles and conveyors that handle goods with precision and speed. These robots navigate through the warehouse, automatically locating, retrieving, and storing items based on optimized paths determined by AI algorithms. These algorithms dynamically allocate storage locations and retrieval paths to maximize space utilization and minimize operational time and energy consumption.

The integration of IoT sensors provides real-time monitoring of inventory levels and system performance. These sensors collect data continuously, enabling predictive maintenance and immediate adjustments to ensure smooth and uninterrupted operations. This real-time data collection also supports accurate and up-to-date inventory management, significantly reducing human error and inventory discrepancies.

Key features of the ASS include:

- Space Optimization: Advanced algorithms dynamically allocate storage locations to maximize the use of available space.
- Operational Efficiency: High-speed robotic shuttles and conveyors streamline storage and retrieval processes, increasing throughput and reducing labor costs.
- Scalability: A modular design allows for easy expansion and adaptation to changing business needs, ensuring the system can grow alongside the business.
- Real-Time Monitoring: IoT sensors provide continuous monitoring of inventory and system performance, supporting predictive maintenance and real-time decision-making.
- Energy Efficiency: The system uses energy-efficient components and smart power management strategies to reduce overall energy consumption and support sustainability initiatives.
- Safety and Labor Reduction: Automation reduces the need for manual labor in hazardous or physically demanding tasks, enhancing workplace safety and addressing labor shortages.

The ASS not only enhances operational efficiency but also ensures high accuracy in inventory management, reducing losses due to errors and improving overall productivity. Its design and implementation mark a significant advancement in warehouse automation, setting a new benchmark for future developments in the field. The system is particularly valuable for businesses looking to optimize their warehousing operations, achieve cost savings, and support sustainability goals. Through pilot projects and case studies, the ASS has demonstrated substantial improvements in storage efficiency, operational speed, and cost-effectiveness, making it an essential innovation for modern warehousing solutions

2.2 Problem, context and constraints for the design of Automatic Storage System

2.2.1 General constraints

The design and deployment of the Automated Storage System (ASS) are governed by a multitude of general constraints imperative to its success and seamless integration within existing warehouse frameworks. One of the foremost constraints lies in optimizing storage space without necessitating significant alterations to the warehouse structure, ensuring efficient utilization of available space in both vertical and horizontal dimensions. Budget considerations play a pivotal role, demanding a delicate balance between cost-effectiveness and system functionality to warrant a compelling return on investment, encompassing initial setup expenses, ongoing operational costs, and maintenance expenditures. Integration with prevailing warehouse management systems (WMS) and operational protocols is indispensable, mandating compatibility with existing software and hardware infrastructure to facilitate smooth assimilation and minimize disruptions. The ASS must possess inherent scalability, featuring a modular design capable of facile expansion or contraction in tandem with evolving business requirements, sans extensive modifications or operational downtime. High reliability coupled with minimal maintenance requisites is paramount to circumvent operational disruptions, necessitating predictive maintenance mechanisms to preempt and mitigate potential system failures. Energy efficiency emerges as a critical consideration, underscoring the necessity for energy-efficient components and intelligent power management strategies to curtail overall energy consumption and align with sustainability goals. Compliance with stringent safety regulations is imperative, mandating the inclusion of robust safety features to safeguard workers and mitigate workplace hazards.

Flexibility is essential, enabling the system to accommodate diverse inventory types and sizes while adapting to fluctuating storage demands seamlessly. User-friendliness is paramount, ensuring straightforward operability and facilitating efficient training for warehouse personnel. Stringent data security protocols must be instituted to safeguard sensitive inventory data against breaches and unauthorized access, ensuring data integrity and regulatory compliance. Environmental and regulatory compliance is imperative, necessitating adherence to environmental standards and minimizing the system's ecological footprint. Acknowledgment of physical constraints such as ceiling height, floor load capacity, and aisle width is essential to ensure the system's feasibility and compatibility within the warehouse environment. By meticulously addressing these general constraints, the Automated Storage System can realize its potential as a comprehensive, efficient, and seamlessly integrated solution, enhancing the efficacy, accuracy, and scalability of modern warehousing operations while promoting sustainability and compliance with regulatory mandates.

2.2.2 Dependability constraints

The dependability of the Automated Storage System (ASS) relies on several critical constraints that ensure its reliability, availability, and maintainability. These constraints are fundamental to guaranteeing uninterrupted operation and minimizing the risk of system failure or downtime:

Reliability:

The ASS must exhibit high reliability, meaning it should perform consistently and accurately over time. Reliability constraints focus on minimizing the probability of component failures, ensuring that the system operates as intended under normal operating conditions.

Availability:

Availability constraints pertain to ensuring that the ASS is accessible and operational whenever needed. This involves minimizing downtime and maximizing uptime through redundant components, fault-tolerant design, and rapid recovery mechanisms in the event of failures.

Maintainability:

Maintainability constraints address the ease and efficiency of maintaining and servicing the ASS. The system should be designed for easy diagnosis, repair, and replacement of components to minimize downtime during maintenance activities.

Predictive Maintenance:
Implementing predictive maintenance features is crucial to identify and address potential issues before they lead to system failures. Predictive maintenance constraints involve incorporating sensors and algorithms to monitor equipment health, predict failures, and schedule maintenance proactively.

Fault Tolerance:
The ASS should be fault-tolerant, meaning it can continue operating even in the presence of component failures. Fault tolerance constraints involve redundancy and failover mechanisms to ensure that the system remains operational despite individual component failures.

Redundancy:
Redundancy constraints involve duplicating critical components or subsystems to provide backup in case of failure. Redundancy can be implemented at various levels, including power supplies, communication channels, and storage mechanisms, to ensure continuous operation.

Rapid Recovery:
In the event of a failure, the ASS should have mechanisms in place for rapid recovery to minimize downtime. Rapid recovery constraints involve automated failover procedures, quick component replacement, and efficient restoration of system functionality.

Monitoring and Diagnostics:
Continuous monitoring and diagnostics are essential for maintaining the dependability of the ASS. Constraints related to monitoring and diagnostics involve implementing sensors, logging mechanisms, and diagnostic tools to detect issues early and facilitate troubleshooting.

Documentation and Training:
Comprehensive documentation and training are necessary to ensure that maintenance personnel are adequately trained to diagnose and repair issues promptly. Constraints related to documentation and training involve developing detailed manuals, procedures, and training programs.

Vendor Support:
Vendor support constraints entail establishing agreements with vendors for timely support and access to spare parts. Having reliable vendor support ensures quick resolution of issues and minimizes downtime during maintenance and repair activities.
By adhering to these dependability constraints, the Automated Storage System can maintain high reliability, availability, and maintainability, ensuring uninterrupted operation and maximizing productivity in warehouse operations.

2.2.3 Real-time constraints
Real-time constraints are pivotal considerations guiding the design and deployment of the Automated Storage System (ASS), ensuring its responsiveness and effectiveness in dynamic warehouse environments. These constraints dictate the system's ability to process inputs, execute commands, and synchronize operations within specified time frames, thereby optimizing efficiency and accuracy. Response time constraints necessitate swift processing of storage and retrieval commands to meet operational demands promptly. Simultaneously, data processing speed constraints require rapid analysis of incoming data from sensors and IoT devices to maintain accurate inventory records and enable informed

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decision-making. Control loop timing constraints mandate continuous adjustment of system parameters to optimize workflow seamlessly. Synchronization constraints ensure harmonized operations among different components, preventing conflicts and bottlenecks. Low data communication latency is imperative for real-time coordination between system elements, facilitating timely responses and seamless integration. Event triggering constraints drive proactive measures in response to changing conditions, such as automated replenishment processes triggered by inventory level thresholds. Predictive analytics constraints enable the system to anticipate demand fluctuations and optimize resource allocation accordingly. Safety response time constraints demand immediate action in the event of safety hazards to safeguard workers and prevent accidents. Feedback loop timing constraints facilitate precise control and monitoring of system performance, ensuring optimal operation. Continuous monitoring constraints enable the system to detect anomalies and faults in real-time, allowing for timely corrective actions. By adhering to these real-time constraints, the Automated Storage System maintains optimal performance, responsiveness, and reliability, enabling efficient and accurate warehouse operations amidst dynamic operational demands.

2.3 Research and analysis of Automatic Storage System

Certainly, there's a wealth of research on automated storage systems and warehouse automation conducted by various scholars and institutions. Here are a few examples:

"Design and Evaluation of Automated Storage and Retrieval Systems (AS/RS) in Automated Warehouse Environments" by Amr Eltawil and Mohamed Moselhi, published in the International Journal of Production Research. This research focuses on the design and evaluation of Automated Storage and Retrieval Systems (AS/RS) in warehouse environments, considering factors such as system layout, material flow, and operational efficiency.

"Optimization of Automated Storage and Retrieval Systems: A Literature Review" by Masoud Rabbani, published in the Journal of Industrial Engineering International. This paper provides a comprehensive literature review on optimization techniques for Automated Storage and Retrieval Systems (AS/RS), covering topics such as system design, throughput optimization, and inventory management.

"Robotics and Autonomous Systems in the Warehouse: A Review and Challenges for Future Research" by Rene van den Brink, Iris F.A. Vis, and Iris F.A. Vis, published in the International Journal of Production Research. This review article examines the role of robotics and autonomous systems in warehouse operations, discussing current trends, challenges, and opportunities for future research.

"Automated Storage and Retrieval Systems (AS/RS) in Warehousing: A Review" by T. C. Edwin Cheng, published in the International Journal of Production Economics. This review paper provides an overview of Automated Storage and Retrieval Systems (AS/RS) in warehousing, discussing their types, applications, benefits, and challenges.

"Integration of Autonomous Mobile Robots in Warehouse Logistics: A Literature Review" by Matthias Grothaus, Michael ten Hompel, and Julian Karst, published in the International Journal of Production Research. This literature review explores the integration of autonomous mobile robots (AMRs) in warehouse logistics, covering topics such as navigation, task allocation, and human-robot collaboration.

These are just a few examples of the research conducted in the field of automated storage systems and warehouse automation. Researchers continue to explore innovative technologies, optimization techniques, and operational strategies to improve the efficiency, flexibility, and reliability of warehouse operations.

2.3.1 A Review and Challenges for Future Research" by Rene van den Brink, Iris F.A. Vis, and Iris F.A. Vis

Abstract---Research on human eye image processing and iris recognition has grown steadily over the last few decades. It is important for researchers interested in this discipline to know the relevant datasets in this area to (i) be able to compare their results and (ii) speed up their research using existing datasets rather than creating custom datasets. In this paper, we provide a comprehensive overview of the existing publicly available datasets and their popularity in the research community using a bibliometric approach. We reviewed 158 different iris datasets referenced from the 689 most relevant research articles indexed by the *Web of Science* online library. We categorized the datasets and described the properties important for performing relevant research. We provide an overview of the databases per category to help investigators conducting research in the domain of iris recognition to identify relevant datasets.

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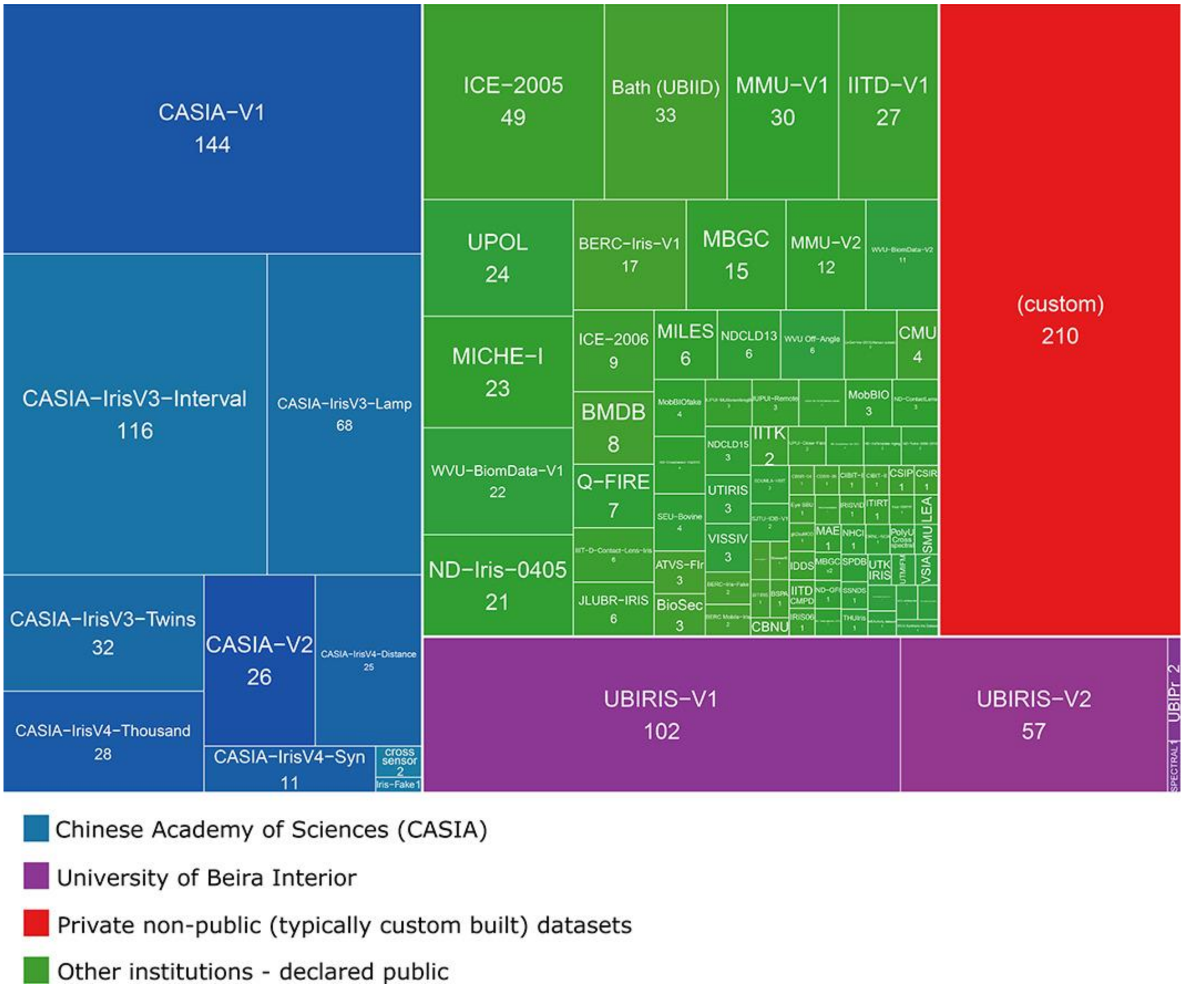

Graph 2.3,1:Graphically Abstract

2.3.1.1 Introduction

Publicly available datasets of human iris images play a major role in research into iris recognition. Most of the available datasets share a substantial number of properties (e.g., near- infrared imaging) and meet the requirements of the widespread and de facto standard recognition method introduced by John Daugman [1]. With the recent popularity of mobile computing and deep learning in biometrics, new databases have been introduced, containing more challenging images of irises. It can be difficult for newcomers to the iris recognition field to identify the major and appropriate databases suitable for their research topics. When entering or conducting research in biometrics, researchers typically go through an extensive amount of published work to identify the state-of-the-art methods, data sources, and benchmark datasets. However, many of the datasets, either very popular benchmarks or niche datasets, are not available, despite the claims of the authors, due to a variety of reasons. Although there are public search engines[1] providing access to freely available research datasets, biometric datasets are typically not included. Due to the personal nature of the data, the dataset providers typically allow their use only for noncommercial research purposes. In addition, authors typically follow the access carefully and require a signature from the researcher or a legal representative of the research institution. This adds additional constraints that limit the popularity of certain datasets among researchers.

The main purpose of this work is to help navigate among the 158 databases used in iris recognition research that are often declared to be publicly available or not explicitly stated otherwise. In this paper, we review existing and publicly

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available (for research purposes) datasets of human irises. We categorized the datasets based on the research areas for which they are suitable. In particular, we focus on the imaging process with respect to current trends in imaging. We created a list of the databases by (i) reviewing the relevant journal papers indexed by the *Web of Science* library and (ii) by searching through online search engines. We also analyze the popularity of the databases and, based on that analysis, we discuss trends in iris imaging. Within the analysis, we also critically reviewed the databases to understand their suitability for particular iris recognition research tasks.

In addition to reviewing the datasets, we also attempted to identify the original reference (the first publication, if it exists) introducing the dataset as well as the earliest research performed and published using the dataset. We also report the number of classes and iris images contained in each dataset, as these are often the most important properties (for data-driven research, e.g., machine-learning approaches).

We reviewed 689 papers on iris recognition or related research from the most relevant journals. Based on the review, we aim to answer the following research questions (RQs):

1. RQ 1: What are the existing and available databases?
2. RQ 2: What are the most popular iris databases?
3. RQ 3: What are the differences, downsides, and commonalities among the databases?
4. RQ 4: What are the common properties of the popular databases?
5. RQ 5: What areas in the field of iris recognition lack an available database?
6. RQ 6: What are appropriate recommendations for creating an iris database?

The rest of this article is organized as follows. Section 2 provides a description of related work, mainly other reviews or surveys related to iris recognition. In section 3, we present the results of a bibliometric analysis where we answer RQ 1 and RQ 2. Section 4, reviewing existing databases and answering RQ 3, presents a critical review and comparison of existing iris databases. In section 5, we describe common attributes of the popular databases, answering RQ 4. In section 6, we discuss limitations and areas with underdeveloped datasets (answering RQ 5) and formulate general recommendations for creating new datasets (RQ 6) to reach scientific relevance (section 8).

2.3.1.2. Related work

There are multiple review papers on the topic of iris recognition and eye image processing. These surveys focus on processing and recognition and devote only a limited space to discussing available datasets.

Nguyen et al. [2] provided an extensive survey of long-range iris recognition. They discuss existing systems and their limitations; however, they only briefly discuss three publicly available datasets, MBGC, UBIRIS V2.0, and CASIA-Iris-Distance. The authors discuss limitations of the recognition methods. However, it is not clear whether the presented datasets are sufficient for future research (e.g., due to limitations in hardware, mainly sensors and optics).

Alonso-Fernandez & Bigun [3] reviewed research related to periocular biometrics. The authors briefly describe five publicly available iris datasets and four periocular datasets (often also used for iris recognition research, although the captured iris is typically very small, 50 pixels). The authors also point out the limitations of sensors and see a future for imaging at a distance, but do not explain why the selected databases would have future perspectives.

While Farmanullah [4] provided an extensive review of segmentation methods for non-ideal and unconstrained biometric iris systems, together with results on 21 datasets, he omits any description of the datasets used or reasons for selecting them.

De Marsico et al. [5] provided a survey of machine-learning methods for iris recognition. While the authors provide results on 11 publicly available datasets, actual comparisons and descriptions of the datasets are absent. While most of the results are performed on the CASIA Iris Dataset v.1, they concluded that more extensive experimentation on the later datasets is needed.

In their survey on understanding iris images, Bowyer et al. [6] selected and described 10 datasets. However, one of them is no longer available (BATH), and two datasets, ICE2005 and ICE2006, are available only within a much larger dataset, ND-IRIS-0405, where it is not clear which files correspond to which particular datasets.[2]

Neves et al. [7] described biometric recognition in surveillance scenarios. The authors refer to four iris datasets with limited descriptions. They refer to the datasets as the main biometric datasets; however, as we show later (see Section 3), there are other datasets with higher significance (in terms of impact) for the research community.

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Rattani and Derakhshani [8] provided a survey of methods for ocular recognition in the visible spectrum. The authors describe seven datasets collected in the visible spectrum. However, some datasets mentioned by the authors are no longer available, despite the claims of the original authors of the datasets.[3]

There are other reviews [10], [11] on the topic of iris segmentation and recognition; however, the authors do not discuss available datasets.

2.3.1.3. Popularity of databases

Using the most appropriate dataset for a given problem is a basic assumption for the successful validation of any scientific method. To the best of our knowledge, currently there is no extensive review of available iris image datasets; therefore, it is difficult to select the appropriate dataset. The selection process involves extensive and time-consuming research, which is often a reason for creating a custom dataset instead. Authors typically justify the new database by reviewing a few (up to five) empirically chosen popular databases that are often unrelated to the present research (e.g., [12], [13]).

In this section, we discuss the popularity of iris image databases based on bibliometric research and provide statistical information about the available ones. The popularity of databases helps identify research areas that receive low attention. The quantified popularity of iris databases is also useful as an indicator of research trends and underdeveloped areas. We define popularity as the citation rank within the selected library. Next, we describe our systematic review of the literature.

Owing to space constraints, the complete list of identified databases (with details) and the list of reviewed publications can be found in the supplementary materials.

2.3.1.4 Identification of relevant studies

There are many sources of literature relevant to iris recognition. For the purpose of this survey, we focused on the most scientifically relevant papers, that is, studies that have the highest impact on the research community. Therefore, we selected the *Web of Science* online library, as many of the most-cited publications in iris recognition known to the authors of this study, are indexed by this library.

We selected 1,012 journal articles listed in the *Web of Science* online library. We searched for the simultaneous presence of two keywords: “iris” and “recognition.” We limited the search to (i) English language, (ii) Science Citation Index Expanded, and (iii) only the research areas: COMPUTER SCIENCE, ENGINEERING, IMAGING SCIENCE PHOTOGRAPHIC TECHNOLOGY, OPTICS, TELECOMMUNICATIONS, MATHEMATICAL COMPUTATIONAL BIOLOGY, AUTOMATION CONTROL SYSTEMS, MATHEMATICS, SCIENCE TECHNOLOGY OTHER TOPICS, and ROBOTICS.

2.3.1.5 Primary study selection and study quality assessment

From the 1,012 studies, we selected 689 relevant articles, that is, the articles where authors report the use of at least one iris image database in their research. The relevant articles were selected based on the abstract, description of the experiment (most of the time an experimental results section) and conclusion. We excluded:

• articles that appeared in the search results but are not related to research of the human iris (e.g. studies that referred to the popular *iris flower data set*),

• duplicates or the same studies published in different sources, and

• studies that are related to human iris, but do not use any iris database in the research (review studies, iris enrollment methods, etc.).

Some iris databases (e.g., the CASIA Iris Database) are continuously evolving, and the number of included images is increasing. Despite the existence of release versions of the CASIA database, some reviewed papers have used intermediate versions that do not correspond to any version published online. In such cases, we classified the database to the closest release version available in terms of the number of images.

2.3.1.6 Review results and databases used

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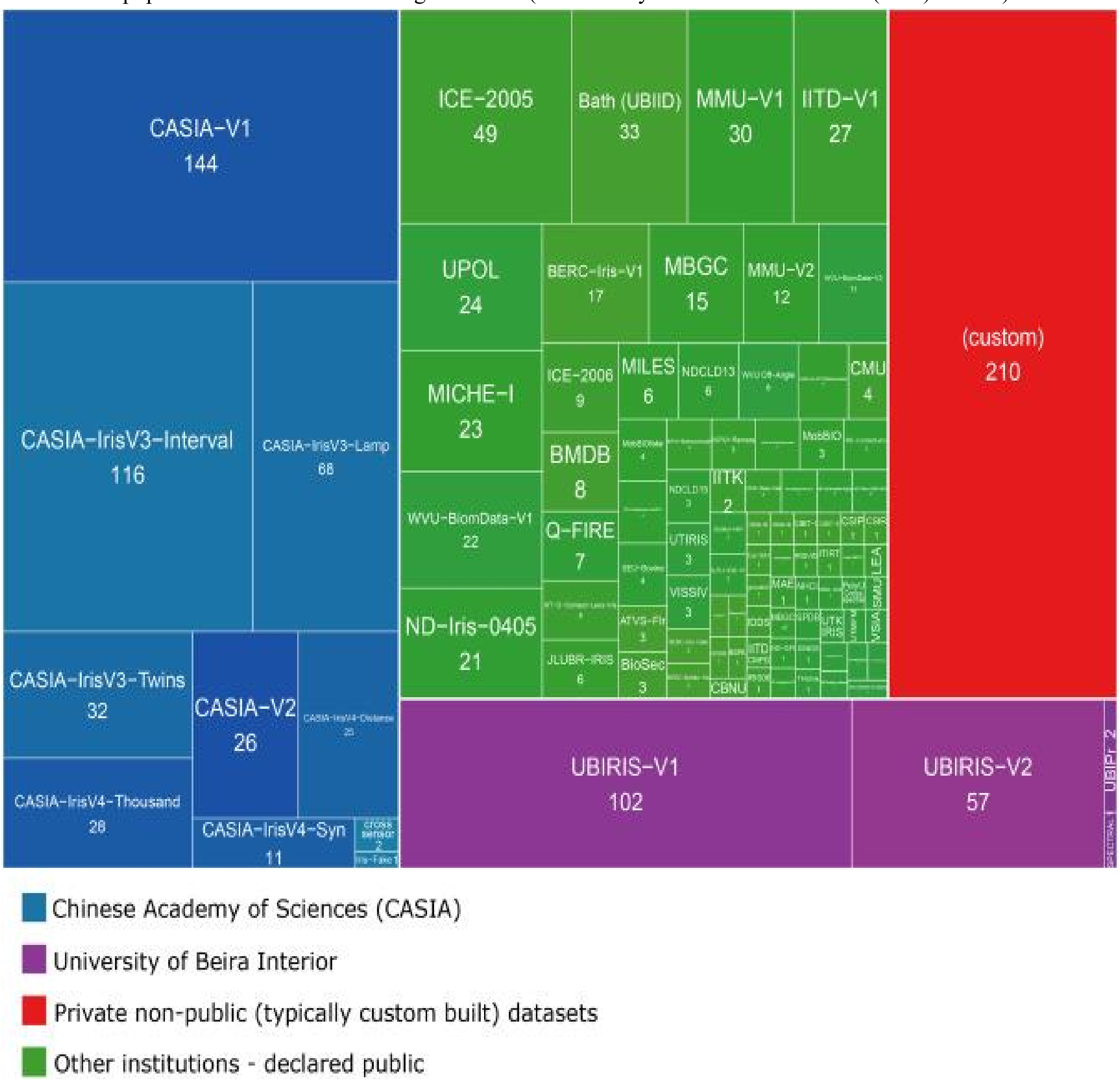
Based on our research, we found that 57.37% (397) of the publications evaluated their method only on one database, and the average number of databases used was 1.87 per publication (see Fig. 2 for more details). 30.35% (210) of publications were evaluated on custom (non-published) databases, where 22.54% (156) publications used only a custom database.

The overall popularity (in terms of uses and citations) of the databases is illustrated in Fig. 1. The iris databases produced by the Chinese Academy of Sciences (CASIA) are the most popular and have been used 453 times in 305 articles, or in more than 44% of the studies. Actually, the CASIA Iris Database v. 1, although being obsolete [14], is still the most popular and most cited iris image database (used mostly as a benchmark in 144 (21%) studies).



Graph 2.3.2: Data base

2.3.1.7 Common properties of popular databases

After identifying the iris databases with the highest impact, we identified four common properties of the most cited databases[17]:

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Longevity - Our findings confirm that the most cited databases have been available for the longest time. A good example is the CASIA-Iris-V1 database, which is the most cited database and has been available continuously since its introduction in 2003. Despite a rather small scale and recommendations not to use it, it is still being cited and often serves as a benchmark dataset. Because there are already many published research papers, this dataset has become a tool for comparing new results with a wide range of past results. In contrast to CASIA-Iris-V1, the extensive BATH database [135] reached only limited popularity mainly due to its relatively short lifespan.

Limited access restrictions - The datasets that are publicly available without requiring researchers to sign a license are more popular (e.g., the UPOL iris dataset [65], [66]). In addition, licenses for many datasets require a signature of the institutional legal representative (e.g., datasets from Notre Dame University [136]. These datasets are less popular than datasets where the signature of an individual researcher is sufficient. (e.g., the CASIA Iris dataset). A license is legally binding a document and typically protects the subjects as well as the institution providing the database. In addition because iris images are a type of personal data, this protection is in many countries regulated and enforced by law (e.g., the EU General Data Protection Regulation [137]).

Scale - The numbers of subjects and images in a dataset also influence the popularity. A sufficient number of samples in a dataset is a significant requirement for performing statistically relevant research. Datasets with more samples (i.e., with higher statistical relevance) can often serve as objective benchmarks. While the size of the dataset is a strong requirement, it is often not sufficient, and other properties, such as a good protocol, must be met as well.

Timing - We found that the most popular datasets introduced novel aspects and enabled research that was not possible with the public datasets available prior to their publication. Good examples are *(i)* the CASIA-Iris-V1 dataset–the first publicly available iris dataset, *(ii)* the UBIRIS v.1 dataset–the first database to introduce unconstrained imaging, and *(iii)* the UPOL [65] database–the first that contains high-resolution images taken in the visible spectrum.

2.3.1.8 Challenges and competitions

Objective and independent evaluation helps in comparing scientific methodology, and ultimately stimulates the progress within particular domains. The iris recognition method introduced by J. Daugman [45], has been the baseline for years; this is in part due to its simplicity and near perfect recognition rate when combined with appropriate imaging. Numerous improvements have been proposed, however, even with this well-defined baseline the results have varied tremendously; a result of the implementation methods, datasets, and evaluation protocols used [6]. These differences prevent objective comparison between methods, a problem which is amplified by the frequent unavailability of the dataset itself, the effect of which is highlighted in section 3.

Many of these problems can be prevented through the creation of benchmark datasets and independent evaluation. This guarantees the objective comparison between methods through both unified protocols and conditions. Such evaluations are typically organized in the form of competitions and/or challenges. In addition to the creation of publicly available datasets with uniform metrics, this solution encourages competition among researchers.

Details of existing competitions and challenges are beyond the scope of this review, hence in Table 16 only the most popular challenges are presented; grouped in terms of the number of participating research teams, and sorted chronologically. Further details can be found in the following review articles [5], [155], [156], [157].

Challenge	Focus	Year	Participants submitted (registered)
ICE 2005 [103]	all stages of iris recognition	2005	9
ICE 2006 [102]	all stages of iris recognition	2006	14
Empty Cell	on large scale		
NICE-I [158]	iris segmentation in an	2008	(97)
Empty Cell	unconstrained environment		
MBGC v. 1 [111, 112]	still & portal (walk through)	2008	14 (68)
Empty Cell	face and iris recognition		
MBGC v. 2 [111, 112]	still & portal	2009	13 (78)
Empty Cell	face and iris recognition		
NICE-II [159]	iris feature extraction and	2010	(67)

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	matching		
Empty Cell	in an unconstrained environment		
ICB ICIR 2013 [160]	iris recognition in real-world applications	2013	8
LivDet 2013 [90], [161]	iris liveness detection	2013	3
Empty Cell			
MobBIO 2013 [162]	iris recognition using portable devices	2013	2
MICHE-I [56]	mobile iris recognition and segmentation	2014	6
Empty Cell	using consumer devices		
MobILive 2014 [163]	mobile iris liveness detection	2014	6
CCBR CCIR 2014 [164]	iris recognition in real-world applications	2014	–
ICB CSIR 2015 [81]	cross-sensor iris recognition	2015	–
LivDet 2015 [91], [161]	iris liveness detection	2015	4
Empty Cell			
SSBC 2015 [165]	sclera segmentation	2015	4 (10)
MICHE-II [60]	mobile iris feature	2016	7
Empty Cell	extraction		
Cross-Eyed 2016 (IJCB) [71]	iris and periocular recognition across spectra	2016	3
BTAS MIR 2016 [54]	mobile iris recogniton	2016	3
ICIP 2016 CMOBR [49]	mobile ocular recognition	2016	4
SSRBC 2016 [166]	sclera segmentation and recognition	2016	3 (12)
Cross-Eyed 2017 (IJCB) [167]	iris and periocular recognition across spectra	2017	5

Table 2,3.1:Competitions and challenges related to iris recognition.

2.3.1.9 Conclusions

The aim of biometric datasets is to enable the testing of biometric systems or methods. The publicly available datasets, serving as benchmarks, enable objective and reproducible research. Despite the claims of the authors, many of the datasets declared publicly available are not available, for a variety of reasons.

In this paper, we reviewed the existing iris image datasets. We focused mainly on the availability and popularity of the datasets. We raised six different RQs. We identified 158 different datasets, of which only 81 were actually available (answering RQ 1). The full list is provided in the supplementary materials. We identified that databases created by CASIA are the most cited (answering RQ 2). We provided descriptions of the available databases in a structured form (answering RQ 3; see Section 4). Subsequently, we identified common properties of popular databases in Section 5 (answering RQ 4). In Section 6, we discussed the limitations of the databases and areas lacking in available databases. Lastly, based on our review, we formulated appropriate recommendations for creating an iris database in Section 8.

A limitation of this study is that we searched only the Web of Science online library when performing the bibliometric research. Another limitation is that we relied on e-mail and phone contacts when obtaining the dataset.

We aspire to bring clarity in the availability of databases to support reproducible research. However, new databases are continuously being created, while others become unavailable. This requires a continuous effort to keep track of the state-of-the-art and popular databases. We plan to keep this list updated and available on our website.[18]

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III. SYSTEM DEVELOPMENT

3.1 Components used in project

- ARDUINO
- SMPS
- SERVO MOTOR
- DRIVER(A4988)
- CNC SHIELD
- HC-05 BLUTOOTH MODULE
- LIMIT SWITCH

3.1.1 Arduino

Arduino is a versatile open-source electronics platform renowned for its user-friendly hardware and software components. At its core is a programmable microcontroller board coupled with an integrated development environment (IDE), simplifying code writing and deployment. Arduino's appeal lies in its accessibility, serving as an invaluable tool for prototyping, hobby projects, and educational endeavors. Its microcontroller board, often featuring an AT mega chip, offers an array of input/output pins for seamless connectivity with sensors, actuators, and peripherals. The Arduino IDE, equipped with a straightforward text editor and essential compilation tools,

Figure 3.1: Arduino

Programming in Arduino employs a simplified language based on Wiring, an abstraction of C and C++, making it approachable even for beginners. An extensive library repository further enhances functionality, offering pre-written code snippets for interfacing with a myriad of components. This versatility extends to countless applications, including robotics, IoT projects, home automation, and interactive art installations. Supported by a vibrant community, Arduino fosters collaboration and knowledge sharing, propelling innovation and creativity. With a wide range of board options, from the popular Arduino Uno to specialized variants, Arduino remains a cornerstone for enthusiasts and professionals alike, democratizing electronics and programming with its accessible and adaptable platform.

3.1.2 S.M.P.S.

A Switched Mode Power Supply (SMPS) is a sophisticated electronic circuit utilized to efficiently convert electrical power from one form to another, commonly found in a diverse array of electronic devices and applications. Unlike traditional linear power supplies, an SMPS employs semiconductor switching devices, such as transistors or MOSFETs, to rapidly switch an input voltage on and off at high frequencies. This switching action enables the conversion of an input AC or DC voltage into a stable output voltage, typically at a different level, while minimizing power loss and maximizing efficiency. The SMPS topology involves rectifying the input voltage to obtain a high-voltage DC signal, which is then switched at high frequency, passed through an inductor or transformer for voltage transformation, and rectified again to produce a regulated output voltage. This regulated output voltage ensures stable power delivery to connected devices, even in the presence of fluctuations in input voltage or load conditions. Key attributes of SMPS include its compact size, high efficiency, wide input voltage range, regulated output voltage, and adaptability to various output voltage and current requirements. These features make SMPS ideal for a multitude of applications, ranging from consumer electronics and telecommunications equipment to industrial automation systems and LED lighting. In

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essence, SMPS technology represents a cornerstone in modern electronics, providing efficient and reliable power conversion solutions for a wide range of electronic devices and systems.

Figure 3.2: SMPS

3.1.3 Servo Motor

A servo motor is a crucial component in many precision-controlled motion systems, renowned for its ability to accurately regulate angular position, velocity, and acceleration. Comprising a motor, feedback device, and control circuitry, servo motors are prized for their precision and versatility in applications ranging from robotics and automation to aerospace and manufacturing. What sets servo motors apart is their ability to maintain precise control over position and speed, facilitated by feedback mechanisms such as potentiometers or encoders. This real-time feedback enables the servo motor to continually adjust its output to match the desired position, ensuring accurate and responsive motion.

Figure 3.3 Servo Motor

Servo motors boast a high torque-to-inertia ratio, allowing them to generate significant torque relative to their size, making them ideal for applications where space is limited. Furthermore, servo motors operate in closed-loop control systems, where the feedback signal is continuously compared to the desired setpoint, enabling rapid adjustments to maintain precise positioning.

Their versatility, fast response time, and variable speed capabilities make servo motors indispensable in industries where precise motion control is paramount. From intricate robotic manipulators to high-speed manufacturing equipment, servo motors play a pivotal role in enabling precise and reliable motion across a wide range of applications.

3.1.4 DRIVER(A4988)

The A4988 is a popular stepper motor driver widely used in various electronic projects and automation applications. As a crucial component in motion control systems, the A4988 enables precise control over stepper motors, facilitating accurate positioning and movement in robotics, 3D printers, CNC machines, and more.

At its core, the A4988 operates by translating digital control signals into precise steps that drive the stepper motor. Its integrated circuitry efficiently manages the current flowing through the motor coils, ensuring smooth and reliable motion. The driver's microstepping capability allows for finer resolution and smoother movement, enhancing the precision of motor control.

One of the notable features of the A4988 is its versatility and ease of use. With adjustable current limiting and decay modes, users can fine-tune motor performance to suit specific requirements. Additionally, its compact size and straightforward interfacing make it accessible for both hobbyists and professionals alike.

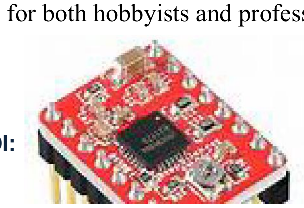

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Figure 3.3: DRIVER(A4988)

The A4988's robust design and thermal protection mechanisms safeguard against overheating and ensure long-term reliability. Its compatibility with various microcontrollers and control systems further enhances its utility in diverse applications.

Overall, the A4988 stepper motor driver stands as a reliable and efficient solution for precise motion control, empowering projects ranging from DIY electronics to industrial automation with smooth and accurate motor operation

3.1.5 CNC Shield

The CNC Shield is a versatile and widely-used interface board designed for controlling stepper motors in CNC (Computer Numerical Control) applications. It serves as an intermediary between a microcontroller, such as an Arduino, and stepper motor drivers, providing a convenient and modular platform for building CNC systems.

At its core, the CNC Shield features multiple slots for plugging in stepper motor driver modules, typically based on Allegro A4988 or DRV8825 drivers. These drivers translate digital control signals from the microcontroller into precise movements of the stepper motors, enabling accurate positioning and control in CNC machines, 3D printers, laser cutters, and other automated systems.

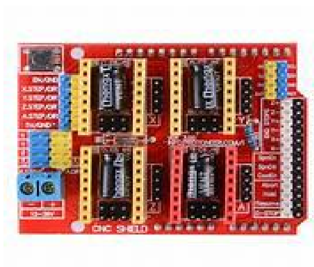

Figure 3.4: CNC Shield

One of the key advantages of the CNC Shield is its compatibility with popular microcontrollers like the Arduino Uno and Mega. This compatibility, combined with the Arduino development environment and extensive community support, makes it accessible to hobbyists, makers, and professionals alike. Users can leverage the rich ecosystem of Arduino libraries and resources to quickly and easily develop custom CNC applications.

The CNC Shield provides convenient features such as onboard stepper motor driver jumpers for setting micro stepping modes and configurable pin headers for connecting limit switches, homing sensors, and other peripheral devices. Its modular design allows for easy expansion and customization, making it suitable for a wide range of CNC projects with varying requirements.

Overall, the CNC Shield serves as a robust and flexible interface board for controlling stepper motors in CNC applications. Its compatibility, versatility, and ease of use make it an essential component for hobbyists, DIY enthusiasts, and professionals seeking to build and customize their CNC systems with ease.

3.1.6 HC-05 BLUTOOTH MODULE

The HC-05 Bluetooth module is a compact and versatile wireless communication module widely used for establishing Bluetooth connections between electronic devices. With its small form factor and ease of integration, the HC-05 module enables seamless wireless communication in various applications, ranging from simple data transfer between smartphones and microcontrollers to more complex Bluetooth-enabled projects such as remote-control systems, wireless sensors, and IoT devices.

At its core, the HC-05 module utilizes Bluetooth technology to establish serial communication (commonly referred to as UART or serial communication) between devices. It features a built-in Bluetooth stack and firmware that support the Serial Port Profile (SPP), allowing devices to communicate over Bluetooth using standard serial communication protocols. This makes the HC-05 module compatible with a wide range of devices and platforms, including microcontrollers, PCs, smartphones, and tablets.

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Figure 3.5: HC-05 BLUTOOTH MODULE

One of the key features of the HC-05 module is its versatility and ease of use. It can be configured as either a master or slave device, allowing it to establish connections with other Bluetooth devices and control the communication process. The module supports various baud rates and communication modes, enabling flexible configuration to meet specific application requirements.

The HC-05 module typically interfaces with microcontrollers such as Arduino, Raspberry Pi, or other embedded systems using UART communication. By sending and receiving serial data over Bluetooth, the module enables wireless control and data exchange between devices, eliminating the need for physical connections and enabling greater flexibility in system design.

Additionally, the HC-05 module often includes onboard status indicators (such as LEDs) and configurable settings (such as device name, PIN code, and communication parameters) that simplify setup and troubleshooting. Its low power consumption and wide operating voltage range make it suitable for battery-powered and low-power applications.

Overall, the HC-05 Bluetooth module serves as a reliable and cost-effective solution for adding wireless communication capabilities to electronic projects. Its compact size, compatibility, and ease of integration make it a popular choice among hobbyists, makers, and professionals seeking to implement Bluetooth connectivity in their projects with minimal effort

3.1.7 Limit Switch

Limit switches are indispensable components in automation and control systems, serving to detect the presence or absence of objects and monitor the position of moving components. Consisting of a mechanical actuator and electrical contacts, these switches trigger a change in electrical state when activated by the movement of machinery or the presence of objects. Mechanical limit switches utilize physical mechanisms like levers or plungers, making them rugged and reliable for harsh industrial environments.

Figure 3.6: Limit Switch

On the other hand, proximity limit switches employ non-contact sensing methods such as magnetic or inductive sensing, ideal for applications where physical contact isn't feasible. Safety limit switches ensure fail-safe operation in safety-critical applications with features like redundant contacts and positive-opening mechanisms. Limit switches are ubiquitous across industries, finding use in machine tools, conveyor systems, industrial automation, elevators, home appliances, and more. Their versatility, reliability, and ease of integration make them indispensable for precise control and safety assurance in a wide array of industrial and commercial applications.

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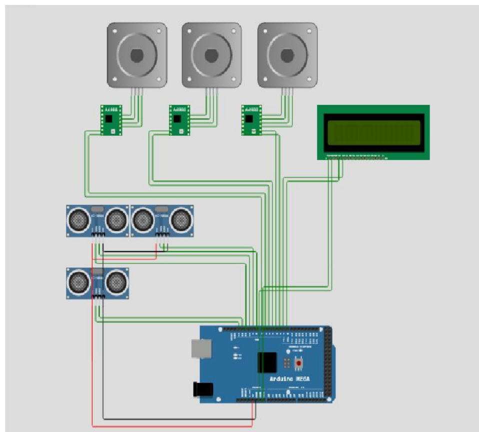
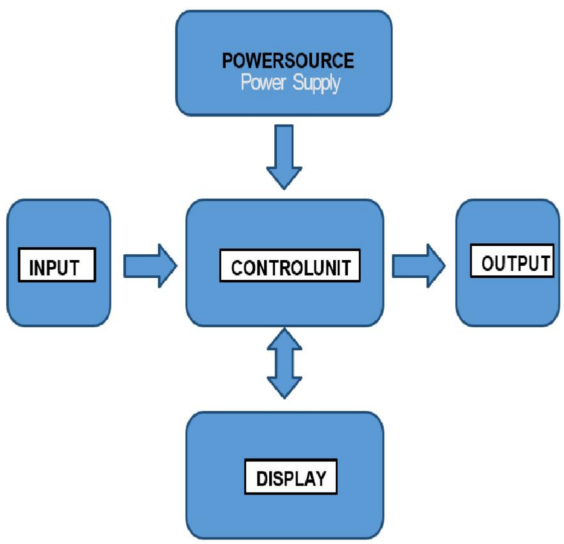
Circuit Diagram of the System

Figure 3.7: Circuit Diagram

- The Arduino board is at the center of the circuit, controlling both the rotary encoder and the stepper motor driver.
- The rotary encoder provides feedback to the Arduino about the rotation of a shaft or wheel.
- The Arduino sends control signals to the stepper motor driver to drive the stepper motor.
- The stepper motor driver controls the movement of the stepper motor.
- Optionally, a brushed DC motor can also be connected to the circuit, with its control handled by the Arduino board



Block Diagram



Block diagram 3.3.1: Power Supply

In this Block diagram:

- The "Control System" represents the overall system that uses the information provided by the limit switch to control the operation of machinery or perform specific actions.
- The "Limit Switch" is the sensor device that detects the presence or absence of an object or monitors the position of a moving component. It provides an electrical signal to the control system based on its status.
- The "Moving Component" represents the part of the machinery or equipment whose position needs to be monitored or controlled. This could be a conveyor belt, a robotic arm, or any other moving part.

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- The "Stationary Object" is the object whose presence or absence is being detected by the limit switch. It could be a workpiece on a conveyor belt, an elevator car in an elevator shaft, etc.

The block diagram illustrates how the limit switch interacts with the moving component and the stationary object. When the moving component reaches a predetermined position or encounters the stationary object, the limit switch is actuated, sending a signal to the control system. The control system then interprets this signal and takes appropriate action, such as stopping the machinery, changing its direction, or triggering another process

This simplified block diagram captures the basic components and interactions involved in a system incorporating a limit switch for position sensing or object detection

3.4 PROGRAM

```
#include<AccelStepper.h>
// Define stepper motor connections and motor
interface type. Motorinterfacetype must be set
to1whenusingadriver:
#definedirPinX2
#definestepPinX3
#definedirPinY4
#definestepPinY5
#definemotorInterfaceType1
//Create stepper motor objects for X and Y axes
Accel Stepper stepper X (motor Interface Type,
Step Pin X,dir PinX);
AccelStepper stepperY(motorInterfaceType,
stepPinY,dirPinY);
voidsetup(){
// Set maximum speed and acceleration forthe
Steppers
stepperX.setMaxSpeed(1000);
stepperX.setAcceleration(500);
stepperY.setMaxSpeed(1000);
stepperY.setAcceleration(500);
Serial.begin(9600);
}
voidloop(){
//Examplemovementcommands
moveToPosition(200, 300); // Move to position
(200,300)
delay(2000); //Waitfor2seconds
moveToPosition(100, 100); // Move to position
(100,100)
delay(2000); //Waitfor2seconds
}
voidmoveToPosition(longx, longy){
stepperX.moveTo(x);
stepperY.moveTo(y);
//Move both motor stothe desiredposition
while(stepperX.distanceToGo()!=0||stepperY.
distanceToGo()!=0){
stepperX.run();
```

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```
stepperY.run();
```

3.5 Hardware List

Table 3.2: Hardware List

Sr. No	Title	Quantity
1	Arduino	1
2	Stepper motor	2
3	A4988 Driver	2
4	Jumper wire	20
5	DC to DC converter	1
6	SMPS	1
7	Trapezoidal ball skewered	2
8	Smooth rod	4
9	Horizontal Support	6
10	Linear bearing	4

3.6 Real Time Data

Real-time data, a cornerstone of contemporary data-driven operations, encompasses information that is promptly generated, processed, and made available for analysis or decision-making, often within milliseconds or seconds of its origination. This data is derived from diverse sources, including sensors, IoT devices, social media platforms, financial markets, transportation systems, and industrial machinery.

For instance, sensors embedded in equipment continuously relay data on parameters like temperature, pressure, and motion, while social media platforms produce vast streams of real-time data through user interactions. Financial markets generate real-time data on stock prices and trading volumes, whereas transportation systems offer insights into vehicle location and route optimization.

Real-time data processing involves the continuous collection, analysis, and visualization of these data streams to extract actionable insights, detect anomalies, and automate decision-making processes. This necessitates the utilization of advanced technologies such as stream processing frameworks, event-driven architectures, and real-time analytics tools.

Applications of real-time data processing span diverse domains, including predictive maintenance, fraud detection, smart city management, e-commerce personalization, and emergency response.

Ultimately, real-time data empowers organizations to gain timely insights, enhance operational efficiency, and respond swiftly to evolving conditions in dynamic environments, thereby driving innovation and fostering agility in decision-making.

Source	Description
Sensor Data	Information from embedded sensors monitoring temperature, pressure, motion, etc.
Social Media Platforms	Real-time data streams generated by user interactions on platforms like Twitter, Facebook, and Instagram.
Financial Markets	Real-time data on stock prices, market indices, currency exchange rates, and trading volumes.
Transportation Systems	Real-time data on vehicle location, route optimization, delivery status, and fleet management.
Industrial Machinery	Data generated by sensors embedded in machinery monitoring production output, equipment status, energy consumption, and resource utilization.

Table 3.3: Real Time Data

IV. PERFORMACE ANALYSIS

Performance Analysis

Performance analysis is a crucial aspect of evaluating and optimizing the efficiency, effectiveness, and reliability of systems, processes, or components. The process begins with clearly defining the objectives of the analysis, whether it's

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improving system throughput, reducing response times, optimizing resource utilization, or enhancing user experience. With a defined scope in mind, relevant data and metrics are collected to provide insights into system performance. This data may encompass response times, throughput, error rates, resource utilization, system availability, and user satisfaction.

Once data is collected, various analysis techniques are employed to interpret the information and identify areas for improvement. Statistical analysis helps uncover trends and patterns, benchmarking compares performance against industry standards, simulation models predict performance under different scenarios, root cause analysis delves into underlying problems, and performance profiling pinpoints areas for optimization.

Based on analysis findings, recommendations are made for enhancing performance, which could involve system optimizations, hardware or software upgrades, process redesign, or configuration adjustments. Following implementation of these recommendations, continuous monitoring and evaluation ensure ongoing optimization, with performance metrics tracked over time to gauge effectiveness.

Performance analysis plays a vital role in enabling organizations to maximize the efficiency, effectiveness, and reliability of their systems, processes, and components, ultimately driving improved performance and operational excellence.

Agility

Agility is the cornerstone of modern organizations, enabling them to navigate rapidly changing environments and capitalize on emerging opportunities. Illustrated in the graph below, agility encompasses several key dimensions: flexibility, adaptability, speed, customer-centricity, resilience, collaboration, and an iterative approach.

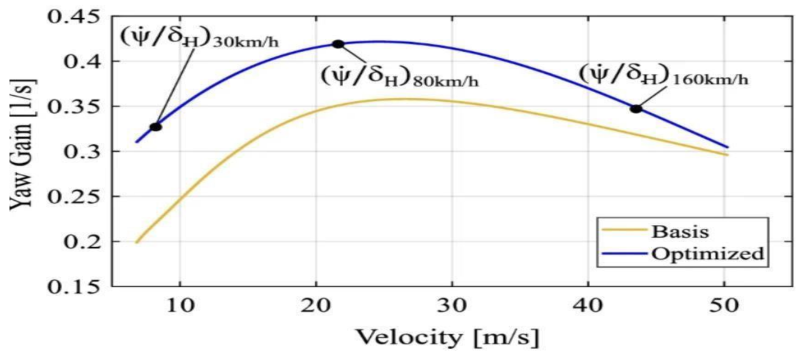


Table 4.1.1: Yaw stability

Flexibility is fundamental, allowing organizations to adjust strategies and operations swiftly in response to evolving market conditions. This adaptability extends to embracing change, fostering a culture of experimentation and learning, and empowering employees to innovate.

Speed is essential in today's fast-paced world, with agile organizations prioritizing rapid decision-making and execution to capitalize on market trends and stay ahead of competitors. By streamlining processes and empowering teams, they accelerate time-to-market and deliver value to customers more efficiently.

Customer-centricity lies at the heart of agility, with organizations focusing on understanding and meeting the evolving needs and preferences of their customers. By leveraging customer feedback and market insights, they develop products and services that deliver exceptional value and experiences.

Resilience is critical for navigating uncertainty and adversity, with agile organizations building robust systems, diversifying resources, and developing contingency plans to mitigate risks and ensure business continuity.

Collaboration and cross-functional teamwork are essential for driving innovation and problem-solving in agile organizations. By breaking down silos and promoting communication and knowledge-sharing, they harness the collective intelligence and expertise of their workforce.

An iterative approach to strategy execution and product development enables agile organizations to test ideas, gather feedback, and make adjustments iteratively. This cycle of experimentation and learning allows them to adapt and evolve rapidly in response to changing market dynamics.

In summary, agility is a multifaceted concept that encompasses flexibility, adaptability, speed, customer-centricity, resilience, collaboration, and an iterative approach. By embodying these dimensions, organizations can thrive in today's complex and dynamic business landscape, driving innovation, growth, and success.

Feedback Control

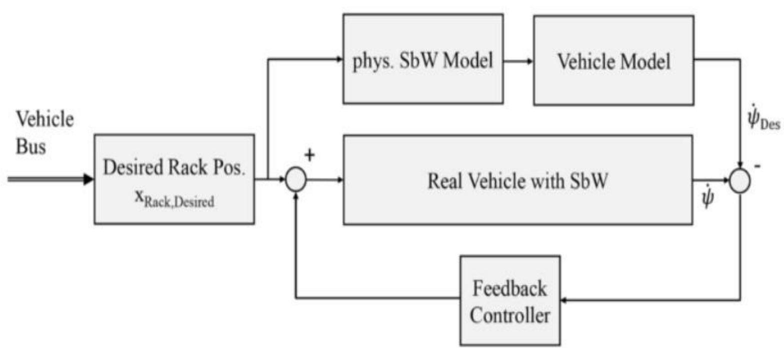
Feedback control is a fundamental concept in engineering and systems theory, playing a critical role in regulating the behavior of complex systems and processes. At its core, feedback control involves continuously monitoring the output or performance of a system, comparing it to a desired reference or setpoint, and using this information to adjust the system's inputs or actions to achieve the desired outcome.

The process of feedback control can be understood through a simple example such as a thermostat controlling the temperature in a room. In this scenario, the thermostat measures the current temperature (the system output) and compares it to the desired temperature set by the user (the reference). If the measured temperature deviates from the setpoint, the thermostat activates the heating or cooling system accordingly to bring the temperature back to the desired level. This continuous monitoring and adjustment process constitutes feedback control.

Feedback control systems can be classified into two main types: open-loop and closed-loop (or feedback) systems. In an open-loop system, the control action is determined solely by the input command without considering the system's output or performance. In contrast, closed-loop systems incorporate feedback mechanisms, where the system's output is fed back to the controller to adjust the input and regulate the system's behavior in real-time.

The advantages of feedback control include its ability to compensate for disturbances, uncertainties, and variations in the system, thereby improving stability, accuracy, and robustness.

Feedback control systems can also adapt to changing conditions and maintain performance over time through continuous monitoring and adjustment.



Block diagram 4.2.1 : Feedback Control

Feedback control finds widespread application across various domains, including industrial automation, robotics, aerospace, automotive, and process control. It is used to regulate parameters such as temperature, pressure, speed, position, and flow rate in diverse systems and processes.

In summary, feedback control is a powerful methodology for regulating the behavior of complex systems by continuously monitoring their output and adjusting their inputs in real-time. Its versatility, robustness, and adaptability make it indispensable in engineering and technology, enabling precise control and optimization of a wide range of systems and processes.

Below is a simplified diagram illustrating the concept of feedback control:

In this Block diagram:

- The "Controller" receives information from the "Sensor" about the current state of the system's output (e.g., temperature, position, speed).
- The "Controller" compares this measured output to a desired reference value or setpoint.

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- Based on this comparison, the "Controller" generates a control signal that determines how the "Actuator" should adjust the system's inputs or actions to achieve the desired output.
- The "Actuator" receives the control signal from the "Controller" and performs the necessary actions to adjust the system's behavior.
- The "System" represents the physical or mechanical process being controlled (e.g., heating/cooling system, robotic arm, automobile engine).
- The "Output" refers to the measured output of the system, which is continuously monitored by the "Sensor" and fed back to the "Controller" for comparison with the setpoint.

This feedback loop enables the system to continuously regulate its behavior in real-time, ensuring that the output remains close to the desired setpoint despite disturbances or variations in the environment.

By continuously adjusting the control signal based on feedback from the system's output, the controller can maintain stability, accuracy, and performance over time

4.3 Result of subjective assessment

In total, 10 subjects were tested, with 4 of them excluded of the Latin square result. The exclusion of three of the test subjects was due to their previous knowledge in a similar test (all three were Phd students in Vehicle Engineering at KTH) and showed different responses on the fault injection compared to the other test subjects. The last test subject was excluded due to problems completing the test and normal driving without fault injection also proved hard.

A learning effect was noticed through the test laps, with the first fault being more severe compared to the other faults throughout all the test subjects.

An example of the ranking of subjective assessment is seen in table 19, where the first row is the severity part (s) and the one below is the controllability part (c). The template used (including the rest of the questions) can be seen in the appendix in section 8.2.

Parameters	Normal driving	Faulty driving	Increment
Lateral acceleration (a_y)	RMS$ay,$normal	RMS$ay,$faulty	RMSinc$_{ay}$
Steering wheel angle (δ_{SW})	RMS$SWA,$normal	RMS$SWA,$faulty	RMSinc$_{SWA}$
Steering wheel velocity ($\dot{\delta}_{SW}$)	RMS$SV,$normal	RMS$SV,$faulty	RMSinc$_{SV}$
Yaw angle (ψ)	RMS$yaw,$normal	RMS$yaw,$faulty	RMSinc$_{yaw}$
Yaw velocity ($\dot{\psi}$)	RMS$yawvel,$normal	RMS$yawvel,$faulty	RMSinc$yawvel$
Yaw acceleration (($\ddot{\psi}$))	RMS$yawacc,$normal	RMS$yawacc,$faulty	RMSinc$yawacc$

Table 4.2: Example of subjective ranking

An analysis was done on the Latin square results and using one-way analysis of variance and covariance (ANOVA) with the test subjects as a group gave a p-value less than $\alpha = 0.05$, the hypothesis that the test subjects means are similar can therefore be rejected. The differences in the test subjects are therefore significant on a 5% significance level.

One-way ANOVA was also done using the failures as a group which showed that for both the severity and controllability on country road at 70 kph as well as highway at 110 kph the pvalue
$= [0.0178, 0.0128, 0.0045, 0.0409]$ was less than $\alpha = 0.05$.

This means that the differences in the failures are significant on a 5% significance level. Using the Matlab function "multcompare" to analyse which fault was different compared to the others showed that for severity on country road at 70 kph, twice the feedback is significantly different to signal delay. For controllability on country road at 70 kph showed that twice the feedback is significantly different to signal delay and opposite feedback. For severity on highway at 110 kph, twice the feedback is significantly different to signal delay and opposite feedback. Finally for controllability on highway at 110 kph twice the feedback is significantly different to signal delay.

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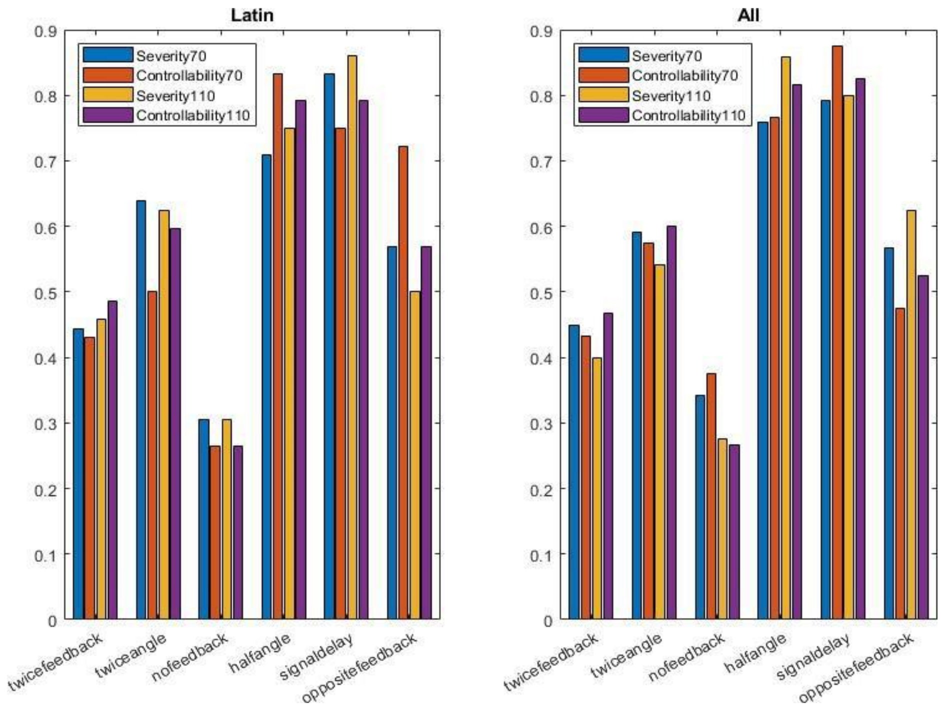
A t-test between severity and controllability as well as between country road at 70 kph and highway at 110 kph was also done, which showed that both the comparisons had differences that are significant on a 5% significance level.

Finally, a normalised ranking was done by ranking the interrelation of each assessment between the test subjects from 1 to 6 and thereafter summing and normalising the value for each failure. The result was illustrated in a divided form of the severity (s) and controllability (c) in the two different speeds, as well as a sum of them. The divided results of the Latin square group and the result for all the test subjects is seen in fig. 20. The summed results for the Latin square group and



Graph 4.3.1: Feedback position

4.3.1 Result of objective assessment

During the test, vehicle data was collected, and the following parameters were used in the objective assessment (table 2).

There are three analysis dimensions, which included six faults, six subjects and two scenarios. All the results were shown and discussed in the following parts.

After processing the data, only a useful period was cut out for analysis, meaning 2 seconds before fault injection and 5 seconds after the fault vanishing. Hence, the x-axis was -2 to 15 s, and the fault vanished at around 10 s. The fault vanishing time was not fixed because the fault was implemented according to vehicle position instead of running time, but this was not a problem for the objective analysis. Furthermore, as shown in figs. 22 and 23, there was a "phase shift" between the first part and second part fault injection. The impact on the results was not obvious because the measurements were calculated using the corresponding reference signal, which meant that if the fault was the first fault introduced during the lap, the first part reference should be used, and vice versa.

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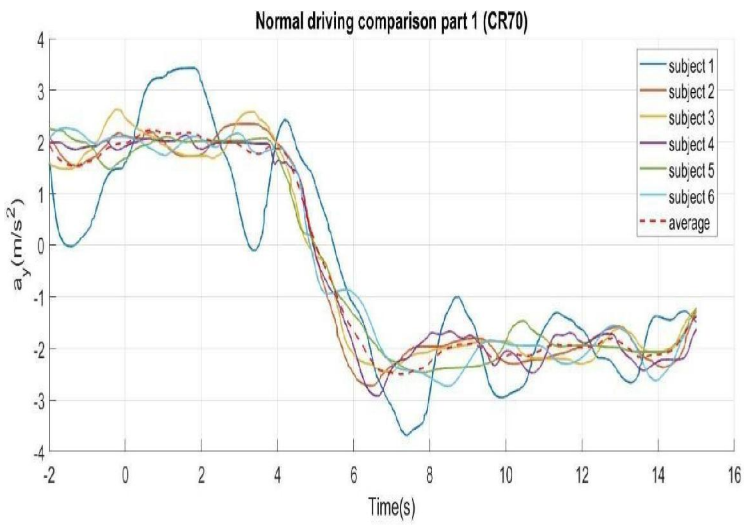

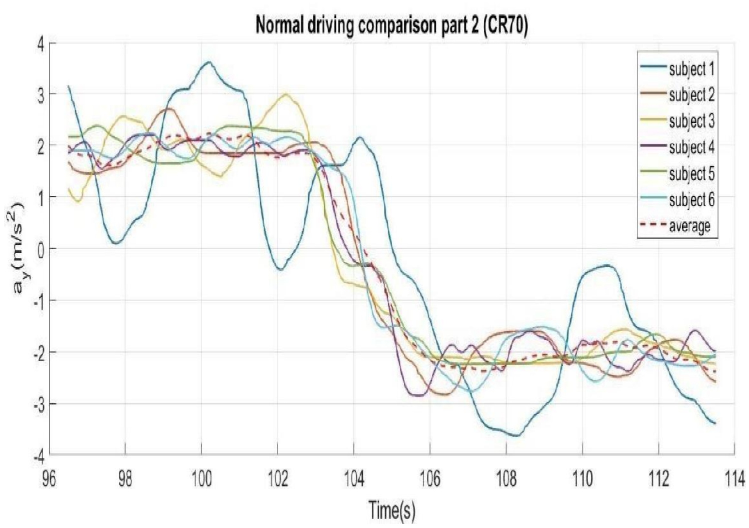

4.3.2 Results of different drivers without faults

Figure 24 plots the lateral acceleration (a_y) signal from S1 and when no faults were injected. According to the figure, driving strategies varied from driver to driver. Subject 4 had excellent controllability of the vehicle, and got used to the vehicle quite fast during the test. However, subject 1 had unstable input during the whole driving, which made subject 1 data seen as a outlier. The red dashed line in both figures is the average value of all the drivers' data. This was supposed to be used as a base line, but replaced by CarMaker data, to avoid the influence from different driving styles. Figure 25 represent the same data but in S2. With higher cruising velocity, the signal oscillated more.

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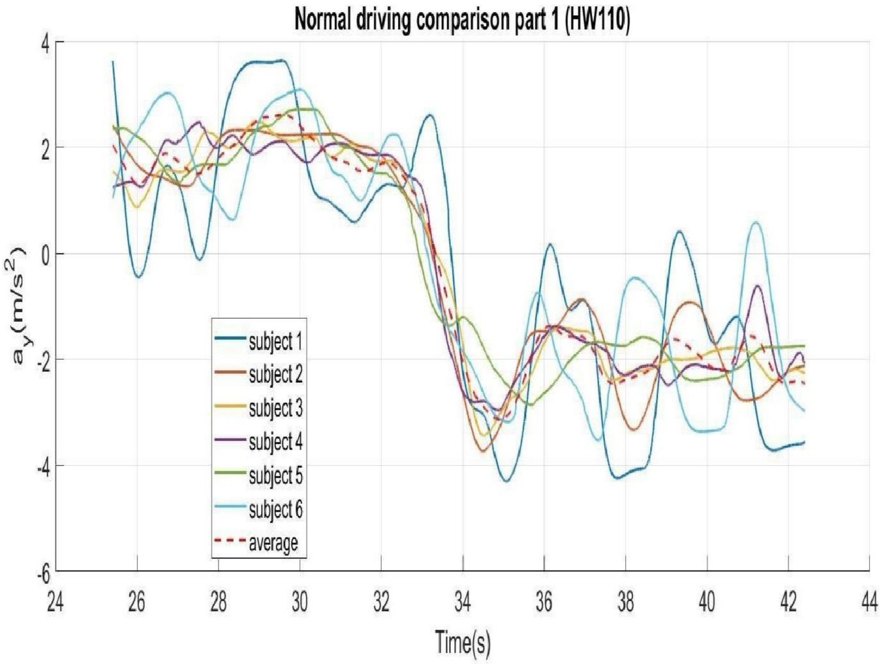

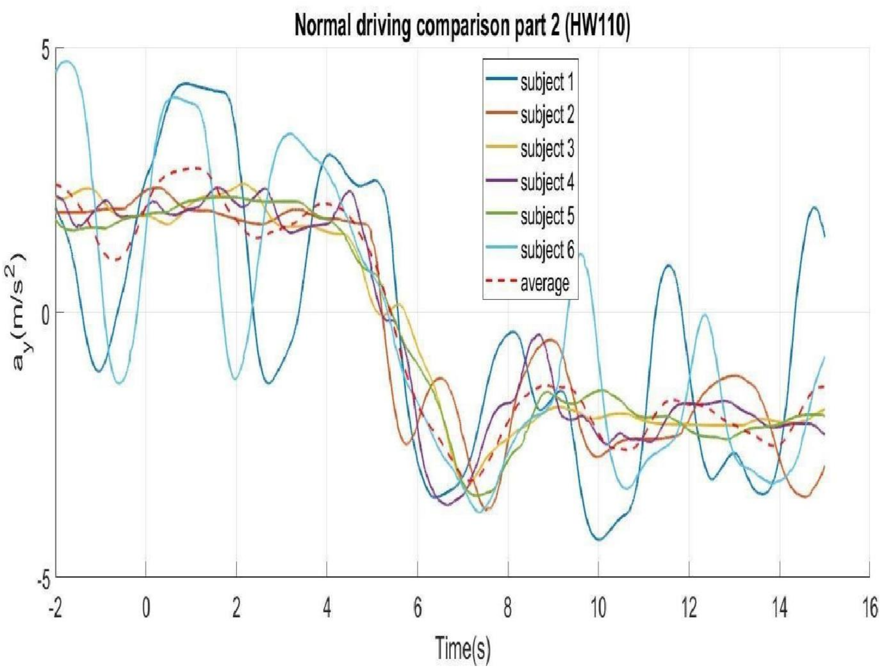

Graph 4.3.3 : Normal driving signal

4.3.3 Results of different faults

With the fault injected, the driving strategies also varied a lot. Figs. 26 to 37 illustrate all the $a_y$data from S1 and S2 classified by faults. The plots are divided into three periods for analysis, which were [0, 5s], [5s, 10s] and [10s, 15s]. Some properties of those faults could be concluded:

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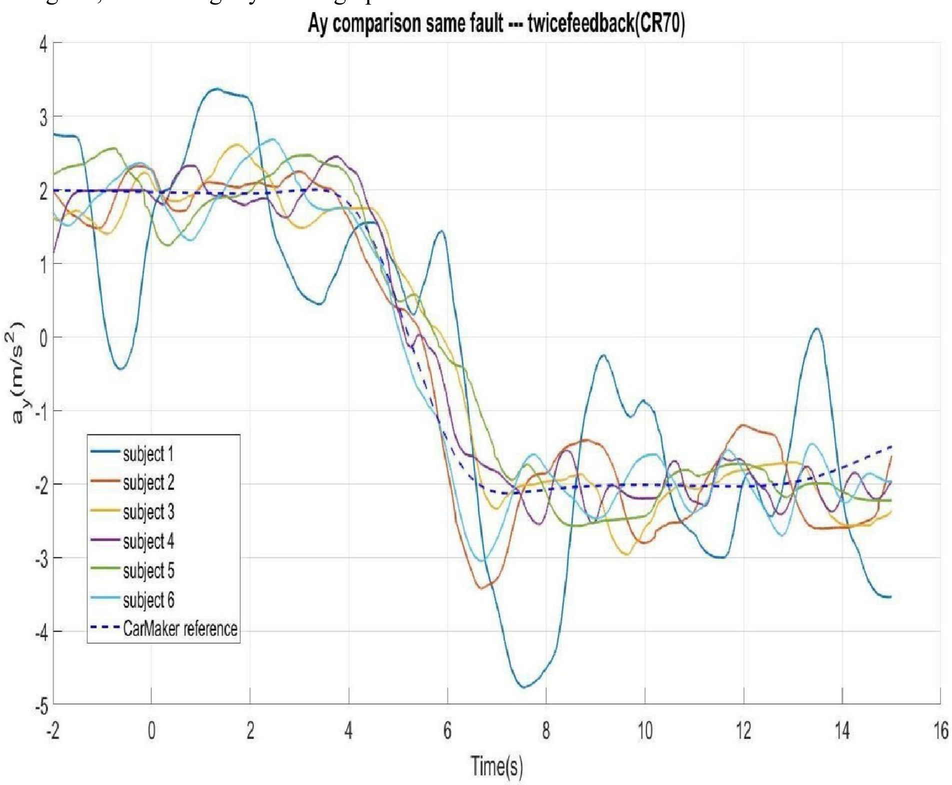
Twiceangle As shown in fig. 26, the drivers performed worst during the 3s after the fault injection due to the sudden change in steering input. When the steering wheel angle input signal was doubled, the feedback force provided to the driver increased simultaneously. Meanwhile, the steering ratio was decreased to half the original value, so the road wheel was more sensitive to the input, leading to more aggressive vehicle behaviour. Since the driver learnt from the steering input, the vehicle oscillated less after 3s. The highway driving, shown in fig. 27, is seen to be harder for the test subjects, with overall larger oscillations.

Halfangle There was also a steering feedback force change when the fault was injected, but the feedback was decreased at 0 s in this case. Since the steering ratio was halved, the drivers got better controllability than twiceangle, illustrated in fig. 28. The impact was not severe **Twicefeedback** Apart from subject 1, drivers had better controllability under this fault, illus- trated in fig. 34. During the test, several drivers could not recognise any change in the steering feel, or felt better with higher feedback torque. One reason was the torque limitation of G29 made the steering feel lighter than on a regular vehicle. Another reason was that higher feed- back torque stiffness provided better on-center feel. The highway driving, seen in fig. 35, show a slightly worse graph with more oscillations.



Graph 4.4: Driving signal faults

Oppos feedback The performance regarding opposite feedback fault varied from person to person, seen in fig. 36. With better reaction capacity and learning speed, the driver could oscillate less. The large oscillation in the beginning is due to the instant switch in torque that surprises the subjects. The highway scenario, seen in fig. 37, show similar trends and no clear differences comparatively.

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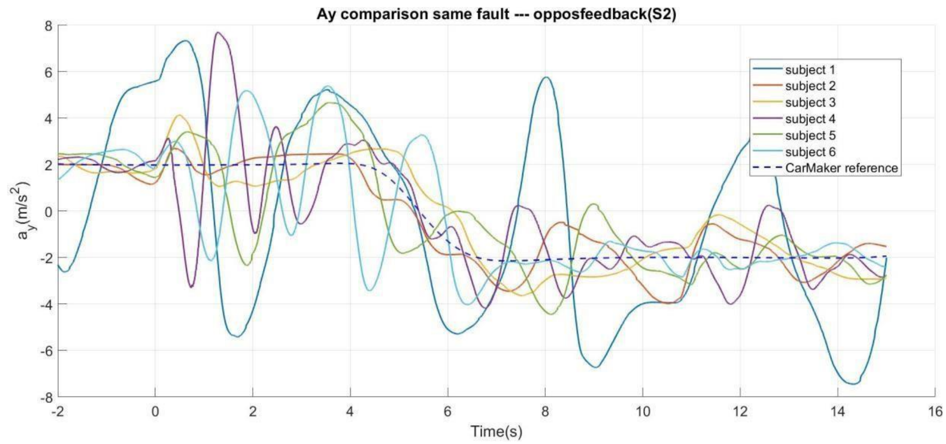
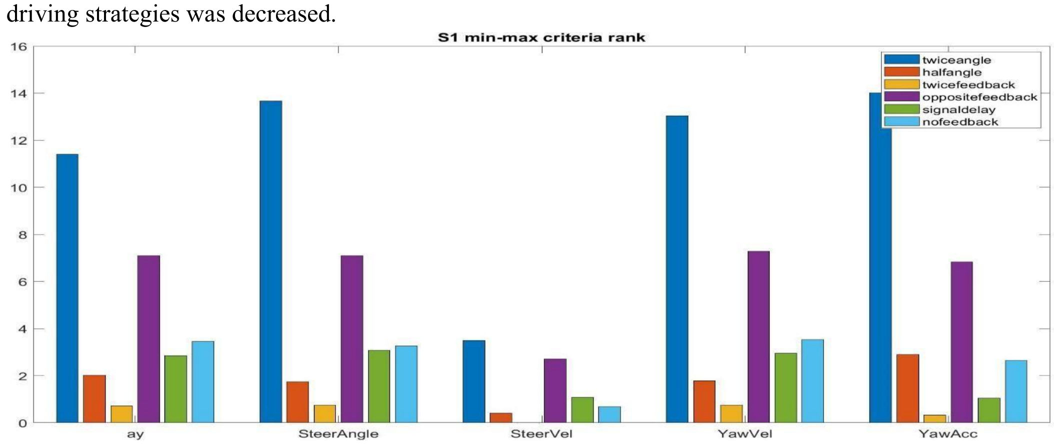


Graph 4.5 :S2 driving ay signal with faults injected—opposfeedback.

4.3.4 Results of calculated criteria

Using the method in section 8.3, the criteria were calculated, partially shown in table 21. Only the incremental measurements were considered during the ranking because they are comparable to each other, and the impact from various driving strategies was decreased.



Graph 4.6: clearty position

4.3.5 Results of faults ranking

To analyse the severity and controllability of all the faults, the measurements were used. The following steps were done before ranking the faults The data from subject 1 was removed because it was seen as a outlier of the odataset.

Within each fault and each measurement, the arithmetic average of all the subjects was taken, which was one row in table 21.

The measurements were classified into four groups according to section 5.3. Due to the different properties of each criteria group, the ranking was done once within each group. There were 4 rankings for each S1 and S2, resulting in 8 rankings. Fig. 39 to 46b illustrate the ranking results of different criteria groups. Lower measurements meant more stable vehicle handling and if the fault occurred during driving, the possibility that a severe accident could happen was lower. Thus, the fault ranking first had the least severity and highest controllability. And the last fault was the most severe one. Moreover, the height of each bar was proportional to the severity of the fault.

4.3.6.1 Min-max criteria rank

The min-max criteria only care about the impact from faults under stationary driving, which means 0 to 4 s. Six parameters are considered in this criteria group, and $a_y$is taken as an example to illustrate the severity of the faults,

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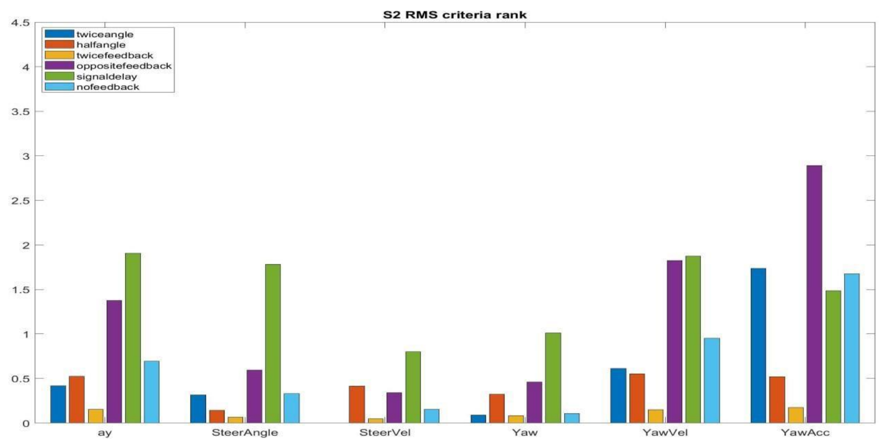
which is shown in fig. 38. One reason is that a_y, steering angle and yawrate of the vehicle typically are proportional to each other, so $a_y$can be a representative parameter.

Another reason is that $a_y$is important when evaluating the vehicle stability. According to fig. 38, the severity rank of the six faults regarding the stationary manoeuvre is shown below, which is the same for both S1 (country road driving, shown in fig. 38a) and S2 (highway driving, shown in fig.

twiceangle >opposfeedback >nofeedback >signaldelay >halfangle >twicefeedback

Fault rank according to minmax criteria group of S1, all parameters. **MS criteria rank**

The rank according to RMS criteria is shown in figs. 42 and 43, and fig. 41 represent the trend of the whole data set. RMS criteria evaluated the severity of both the stationary and non-stationary driving. The measurement value of S2 are smaller than that of S1 for the same reason mentioned previously. The severity rank differs from one parameter to another, for instance, twice angle (the blue bar in fig. 42) ranks 2nd in two parameters, 3rd in three parameters, and 4th in one parameter. It is hard to conclude an explicit result. However, it is obvious that signal delay and opposfeedback are the most severe faults, and twice feedback was the least severe fault. Twice angle, half angle and no feedback have intermediate severity.



Graph 4.7: difference of the position

4.3 Advantages and Disadvantages

4.3.1 Advantages

- Improved Stability: Feedback control helps maintain system stability by continuously adjusting system inputs in response to changes in the environment or disturbances, preventing oscillations or instability.
- Increased Accuracy: By continuously comparing the system's output to a desired setpoint and making adjustments accordingly, feedback control ensures that the system achieves and maintains the desired level of performance or output.
- Robustness: Feedback control systems are inherently robust to variations and uncertainties in the system and environment, as they adapt in real-time to maintain desired performance despite changing conditions
- Adaptability: Feedback control allows systems to adapt to changing operating conditions, requirements, or objectives by dynamically adjusting control parameters based on feedback from the system's output.
- Disturbance Rejection: Feedback control systems can effectively reject disturbances or external influences that may affect the system's performance, ensuring consistent and reliable operation.

4.3.2 Disadvantages

- Complexity: Designing and implementing feedback control systems can be complex, requiring a thorough understanding of system dynamics, control theory, and feedback mechanisms.

- Tuning Challenges: Achieving optimal performance with feedback control systems often requires careful tuning of control parameters, which can be time-consuming and may require specialized expertise.
- Sensitivity to Noise: Feedback control systems may be sensitive to noise or measurement errors in the feedback signal, leading to inaccuracies or instability if not properly filtered or compensated for.
- Delay and Lag: Feedback control systems may exhibit delays or lags between sensing the system's output, processing feedback, and adjusting system inputs, which can impact responsiveness and performance in dynamic environments.
- Risk of Instability: In some cases, feedback control systems may exhibit instability or oscillations if control parameters are not properly tuned or if the system dynamics are highly nonlinear or unpredictable. Overall, while feedback control offers numerous advantages in terms of stability, accuracy, robustness, and adaptability, it also presents challenges related to complexity, tuning, noise sensitivity, delay, and the risk of instability. These factors must be carefully considered and addressed in the design and implementation of feedback control systems to ensure effective and reliable operation.

V. CONCLUSION

5.1 Conclusion

This paper summarizes the various components in an automated storage and retrieval system, lists also the benefits of automating a company's storage operation. Details of the various control strategies are included and a summary of the performance measures applied to such systems. The findings from this overview are that there is currently a large amount of research on-going with particular emphasis on improving throughput by analyzing storage, retrieval and dwell point strategies. The best recorded performance was content a current dwell point, simultaneous travel, dual control, free nearest storage and nearest retrieval strategies selected in combination. In general, dual control improved performance (in terms of throughput), simultaneous travel was found to be better than rectilinear travel, dwell point at origin gave very poor results, and a dwell point at current, pick point or deposit point appears best considers the popularity of items, not their space occupation. COI-based storage is that the volume-based assignment only considers the popularity of items, not their space occupation. The pick volume of an item can be expressed in number of units or pick lines during a certain time horizon. The difference between this method and COIbased storage is that the volume-based assignment only considers the popularity of items, not their space occupation.

5.2 Future work

Regarding future work, a better performing steering wheel, especially in the steering feel area around the on-centre, would directly benefit this kind of experimentation. This could be done by using a better steering wheel that uses another technique than the gear drive that the Logitech G29 uses (for example the direct drive system) and/or implementing a model that deals with the on-center feel in a better way. A wheel with a torque encoder would also be to an advantage. It would also be interesting to have a similar experiment but with a larger sample size. It was noticed that the subjects drove with rather different" techniques" and that with the use of a larger sample size the difference would not propagate that much into the full data analysis. Another thing worth looking into is how to further implement the ISO26262 standard into the thesis. This would need gaining substantial knowledge in the design of the standard. The SBW system I build can be improved a lot, but the main problem seems to be with the choice of controllers and motors. For a future project, given better equipment, this system could be implemented in a small model car and can be used for control theory demonstrations. New control systems, such as state-space controls, can be implemented to enhance the performance of the system. Although not in the near future, given enough resources, this system can be implemented in real roadcars and perhaps be combined with regular steering to take advantage of the safety benefits.

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