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A Project & Master Thesis Report On Design And Creation Of A Swarm Robot

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Abbreviations and List of Symbols

SR	swarm robot or robots por robotics
AI	artificial intelligence
SI	swarm intelligence
AAAI	Association for the Advancement of Artificial Intelligence
VR	Virtual Reality
LR	literature review
SLR	systemativ literature review
TLBO	Teaching-Learning-Based Optimization
GNSS	Global Navigation Satellite System
UUV	Unmanned Underwater Vehicle
RFID	Radio-Frequency Identification
IR	infrared
ADC	Analog-to-Digital Converter
LDR	Light Dependent Resistor
RPC	Remote Procedure Call
SPI	Serial Peripheral Interface
ANT	Advanced and Adaptive Network Technology
SDK	Software Development Kits
AVR	Alf and Vegard's Risc Processor
PCTL	Probabilistic Computation Tree Logic
API	Application Programming Interface
IRACE	Iterated Racing for Automatic Configuration and Evaluation
VCC	Voltage at the Common Collector
GND	Ground

Abstract

SR is relatively a new field that study the coordination abilitty of a swarm of simple robots that be acheived through simple local rules, it is inspired by the collective behavior of social insects intelligence observed in nature. this thesis use three different methodologies to explores the design, creation and simulation of SRs. starting with an examination of the current state of research in SR field, using both traditional and systematic literature reviews, introducing the key trends, gaps, and challenges within the field in the last decade, particularly focusing on the hardware and software components crucial for building functional swarm robots, also it identifies critical gaps and future research directions of the field, and the emergency need of standardization in it. the thesis proceeds to the practical creation of a small-scale swarm robot system consisting of two robots. This experimental section details the hardware design, software architecture, and the implementation of a centralized master-slave algorithm designed to mimic the basic principles of swarm behavior. The limitations of this small-scale implementation are acknowledged. finally the Webots simulator is used as a tool to test the master slave algorithm and follow the leader algorithm.

Key words: swarm robotics, hardware, software, swarm intelligence, Systematic literature review (SLR), Standardization

Chapter 1
Introduction

1.1 Introduction

The world outside our minds is the first source of knowledge for us as human beings. From the moment humans first walked on Earth, nature has profoundly inspired and shaped human thought. It continues to be a source of innovation, influencing everything from the tools we use to the stories we tell. This is because the human brain takes what it perceives from the real world as inputs, then processes it to produce outputs. AI for example as a major branch of science and its impact will be according to expert Kai-Fu Lee predicts “more than anything in the history of mankind.”[1] is reflected as the artificial representation of human brain which tries to simulate their learning process with the aim of mimicking the human brain power[2] so it is a bio-inspiration from human intelligence to artificial intelligence. The Same as “AI”, Swarm robotics is bio-inspired from how the nature swarms it takes inspiration from social insects like ants, bees, termites that coordinate and accomplish complex tasks through self-organization, without centralized control[3][4][5][6][7]. So the SR is an emerging research area that attract researchers since the concept proposed in the 1980s[8] The most promising applications of swarm robots are in domains where it is impossible or too dangerous for humans to enter, the environment is unknown, or the real-time requirements are too restrictive to pre-compute globally optimal solutions. Specific examples could be the exploration of the deep sea, space, or celestial bodies, environmental monitoring, smart traffic concepts, or nano medicine. These visionary applications are further detailed by Schranz et al (2020). [9] Also cooperative control mechanisms for flocking, navigating, and searching. Other complex collective behaviors such as task allocation, path planning, and nest constructing[10].
Google Scholar shows the phrase ”swarm robotics” first appeared in 1991, but saw limited usage until 2003 when it started growing considerably. SCOPUS data also shows a comparable increasing trend (Figure 1). This indicates that while swarm robotics has roots in seminal works from the 1990s, the field only began significantly growing around the year2000.[11]

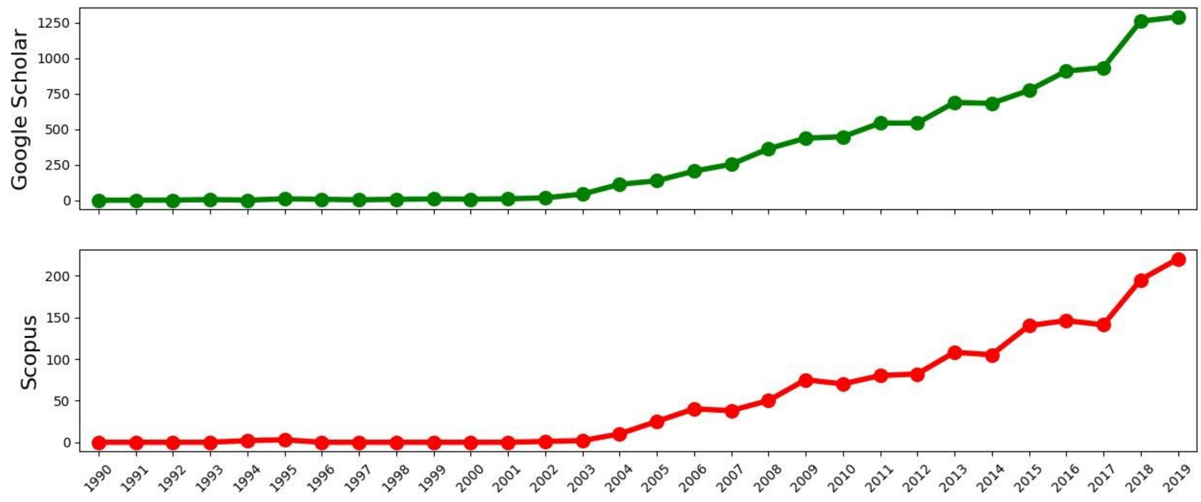

Figure 1.1: Citation count for the search “swarm robotics” in Google Scholar and in SCOPUS. Both show the same tendency, with an exponential growth from year 2000 on.[12]

1.2 Background on swarm robotics:

1.2.1 Definition of swarm robotics:

“It is not surprising that AI is so difficult to define clearly. It is, after all, an imitation or simulation of something we do not yet fully understand ourselves: human intelligence.”[13] the same as AI its difficult to define clearly SR [14]because it is just a simulation of something that we don’t understanding it very well which is swarm intelligence, however there is a very common definition that we can rely on it.
So Swarm robotics is the study of how to coordinate large groups of relatively simple robots through the use of local rules. is an extension of the study of Multi-Robot Systems . It takes its inspiration from societies of insects that can perform tasks that are beyond the capabilities of the individuals such as social insects, fish schools, or bird flocks, characterized by emergent collective behavior based on simple local interaction rules , it demonstrate three desired characteristics for multi-robot systems: robustness,flexibility and scalability.[15][16][17][18][19][20].
The term “swarm” refers to a large group of locally interacting individuals with common goals. It is used to describe all types of collective behaviours even though it brings up associations to joint movement in space.[21].

1.2.2 swarm robotics past, present and future:

In the last two decades, swarm robotics has grown from a small domain initiated by a few studies with a clear biological inspiration to a mature research field involving several labs and researchers worldwide. The phrase ”swarm robotics” made its first appearance in 1991, but its usage remained very limited until 2003 when it started to grow considerably. Initially, the study of swarm robotics was aimed at testing the concept of stigmergy as a means of indirect communication and coordination between robots. Following a few initial attempts, several studies appeared after 2000 focused on tasks such as object retrieval, clustering, and sorting of objects. These studies started from known behaviors observed in social insects and deployed robot swarms demonstrating similar behavior. One of the first international projects to investigate cooperation in a swarm of robots was the Swarm-bots project funded by the European Commission between 2001 and 2005.[22]

In the early 1980s, researchers from Europe and the USA are begun to develop a group of mobile robots like CEBOT(Fukuda, Nakagawa, Kawauchi, &Buss,1989), SWARMS(Beni,1988), ACTRESS (Asama, Matsumoto, &Ishida,1989) and etc. these projects are preliminary.[23]

Other projects that we can cite[24]:

Project SI: was developed by the Embedded Lab of Shanghai Jiaotong University. The project consists of a swarm of mobile robots, named eMouse, controlled by the swarm inspired algorithms.

Sambots: Sambots is a project for a swarm of self-assembly robots. Multiple Sambots can form new structures through selfassembly and self-reconfiguration.

Swarm-bots project:sponsored by the Future and Emerging Technologies program of the European Commission, is a project for exploring the design, implementation and simulation of self-organizing and self-assembling artifacts. The project, lasting 42 months, was successfully completed on March 31, 2005.

Swarmanoid project: Since October 1, 2006, the Swarmanoid project has extended the work done in the Swarm-bots project to three dimensional environment. The team introduced three types of small insect robots: eye-bot, hand-bot, and foot-bot, which differ from s-bots in previous project. Swarmanoid consists of a total number of 60 robots from the three types. The team has won the AAAI 2011 video competition.

Pheromone robotics project: started in 2000, is coordinated by Professor David. The project aims to provide a robust, scalable approach for achieving the swarm level behaviors using a large number of small-scale robots in surveillance, reconnaissance, hazard detection, path finding, payload conveyance and small-scale actuation.

I-swarm project: Hosted by Professor Heinz since 2004, the project combines micro-robotics, distributed systems, and biological swarming to enable mass-production of tiny, low-cost micro-robots. Each robot is less than 3 x 3 x 2 mm in size, moves at 1.5 mm/s, and has limited sensors and intelligence. Over 100 robots cooperate as a swarm, exhibiting emergent complex behaviors. Their small size allows operation within creatures at low cost. The distributed swarm provides sensing and actuation solutions at a micro scale.

E-puck education robot: This project aims to develop a miniature mobile robot for educational use. The robots have a simple mechanical design that is easy to understand, operate, and maintain. They are inexpensive, flexible, and can support a wide range of educational activities through their potential for various sensors, processing power, and extensions. By the end of 2010, over 60 research projects had already utilized the e-puck robot platform. Potential educational fields include mobile robotics, real-time programming, embedded systems, signal processing, image/audio feature extraction, human-machine interaction, and collective/swarm systems.

Kobot project: conducted by Middle East Technical University, is a new mobile robot platform which is a specially designed a swarm robotics. The robots are equipped with an infrared-based short range sensing system for measuring the distance from obstacles to a novel sensing the relative headings of neighboring robots.

Kilobot project: aims to design a robot system for testing the collective algorithms with a population of hundreds or thousands of robots. Each robot is made of low-cost parts and takes 5 min to be fully assembled.

microUSV:is a small platform to validate marine swarm robotics appliances. It features 3D-printed parts and off-the-shelf components to compose its design.[25]

mROBerTO and mROBerTO 2.0: are robotic platforms with advanced computational and sensing abilities to create swarm robotics applications. The advances on this platform allowed the creation of platforms with more reliability and repeatable locomotion.[26]

Tribots: are three-legged robots designed to reproduce complex strategies from ants, including the evasion from large predators. The robots are insect-scaled and easy to assemble. Nonetheless, it allows a set of five different movements.[27]

Swarm robotics holds great potential for future applications. Robots capable of forming decentralized swarms can be used for monitoring, inspection, exploration, and rescue purposes in many environments, including land, sea, and space. Applications include environmental monitoring, disaster response, and precision agriculture, among others. In addition, swarm robotics has the potential to revolutionize manufacturing and logistics, enabling distributed manipulation and transportation of goods and materials, and leading to the development of new types of products and services. There is still much research and development required to reach these applications, but swarm robotics is a growing field, and research efforts are expected to continue to grow, enabling further advancements that can lead to the realization of these abilities.[28]

Year	
1990-2000	A new paradigm is tested in which collaboration is emergent from simple (often bio-inspired) behaviours. First experiments with robots demonstrating self-organisation by means of indirect (stigmergy) and local interactions, with a clear inspiration from swarm intelligence
2000-2005	The possibility to design robots cooperating in a swarm is extended to several new tasks, entailing manipulation of objects, task allocation and tasks that strictly require collaboration to be solved.
2002-2006	The Swarm-bots project demonstrates robot swarms capable of self-assembly, opening to physical forms of collaboration. Robots are capable of building pulling chains and large structures capable of dealing with terrain roughness.
2004-2008	Initial demonstrations of the automatic design of robot swarms by means of evolutionary algorithms, leading to the establishment of the evolutionary swarm robotics approach.
2005-2009	First attempts of developing standard swarm robotics platforms (e-pucks), as well as miniature robots for swarm robotics research (alice, jasmine).
2006-2010	The Swarmanoid project demonstrated for the first time heterogeneous robot swarms composed of three groups of robots: flying, climbing and ground-based robots.
2010-2015	Different approaches appear to the design of robot swarms: advanced methods for the automatic design (AutoMoDe, novelty search), design patterns, mean-field models and optimal stochastic approaches.
2014-2019	The "control without computation" approach develops swarm robotics behaviours with direct sensor-actuator mapping and no computation whatsoever.
2016-2020	Swarms of flying drones become available for research, and decentralised solutions are studied and deployed.
2020-2025	First demonstration of robot swarms capable of autonomously learning the best collective behaviour for any given problem.
2020-2030	First civil applications of robot swarms to precision agriculture and infrastructure inspection and maintenance. Military applications largely use non-offensive unmanned drones for mission support.
2025-2040	First space exploration mission on the Moon and Mars with miniature rovers, expanding the explored area and demonstrating onsite construction abilities.
2030-2050	Miniature robot swarms are demonstrated for target

1.3 Overview of biological inspirations from social insects :

as we see above in the beginning of the thesis SR like every other ideas and innovations in the human history it gets its inspiration from nature.
So SR is inspired from how nature swarms [29][30][31][32][33], It's difficult to imagine how such sophisticated abilities can emerge from simple local rules and simple individuals with limited cognitive and communicating abilities Nevertheless, in the most cases, one creature from the same spicies can never accomplish such complex task but a swarm can do it easly without any pre-planning.[34]
Swarm intelligence was introduced by Gerardo Beni and Jing Wang in 1989 with their study of cellular robotic systems[35][36]. Swarm intelligence is a biological phenomenon in which groups of organisms or participants forming real-time systems[37]. It is an emergant propriety that arises when social species work within a swarm to accomplish a desired goal, individuals don't need nearly any knowledge to produce this complex behavior they aren't informed about the global status of the swarm there is no leader no ID's no centralized network[38], it is based on the concept of locality and it is decenralized the implicit communication is donne by the changes made in the environment and that called stigmergy[39][40]. So the Swarm use two different types of communication to achieve a desired goal one through the interaction robot-robot the other is robot-environment[41]. Moving together within a swarm increase the chance of surviving swarm behavior fits more than individual behavior in terms of surviving and food gathering...etc.[42]
Let's see some examples of nature swarming that inspired researchers in the last two decades:

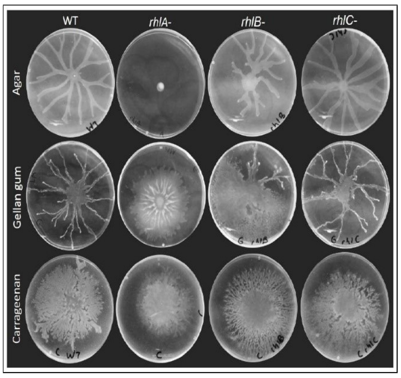

Figure 1.2: swarm behavior in bacteria colonies[43]


Figure 1.3: swarm behavior fish schools[44]

Figure 1.4: swarm behavior in birds[45]

Figure 1.5: swarm behavior in ant colonies[46]

Fig1.2 : bacteria colonies: Microorganisms like bacteria frequently exhibit collective behaviors by forming multicellular communities called biofilms. Within these biofilms, bacteria engage in intercellular communication through the exchange of molecular signals. biofilms can optimize their population's survival chances and in their resistance to antimicrobial agents compared to individual can be up to 500 times greater.[47]
Fig1.3: fish schools : is a phenomena represent a collective behavior of a swarm of fishes tha can provide for them a defense mechanism against the predators, better foraging and increase the hydro-dynamic efficiency in long distance migration events. the fishes are able to stream up and down collectively at impressive speeds and make changes of the overall shape of the swarm without any collision as if their motions were choreographed using their sensors to interact locally with neighbors and also the schooling marks on their shoulders.[48][49]
Fig1.4: bird crowds : Migratory birds assemble into coordinated flocks and use multiple sensory cues to navigate and locate destinations during their long-distance journeys like sun compass, time calculation and magnetic fields[50]. They swerve to another direction in unity then suddenly to another and swoop down to the ground, how they can do that? Researchers like Reynolds [51] suggests a model called 'boid' model to simulate the motion of bird crowds and propose those 3 local rules (avoidance rule, copy rule, center rule) to help the emerge of swarm behavior then flake added another one (view rule) [52]
Fig1.5: ant and bee colonies : social insects are the original source of this emerging research field because the rest of swarming creatures shares similar collective properties with them.[53] Ants communicate through pheromones, sounds, and tactile interactions. Successful foragers mark the shortest path on their return with a pheromone trail. More ants follow reinforced trails, gradually optimizing the route. Research

suggests ants can specialize in roles based on past performance. Those with higher foraging success intensify their efforts, while others reduce foraging or transition to different tasks.[54]

1.4 Applications and advantages of swarm robotics systems :

There are many advantages and possible applications that make swarm robotics a promising technology for various fields.

1.4.1 Advantages:

-single robots: single robots have a complicated structure and control modules resulting a high cost of design, construction and maintenance. They are also vulnerable especially when it has broken parts which affect the whole system, the tasks are very complex when a single robot deal with it.[55]
-swarm robots: comparing to single robots SR have simple structure, easy to control, low cost of design, construction and maintenance.
Swarm robots have those characteristics that give the overall swarm very advanced advantages facing complex problems:[56][57][58][59]
*scalability : is the ability to expand a self-organized mechanism to support larger or smaller numbers of individuals without impacting performance considerably.
*adaptability :can handle dynamic and stochastic environments due to the decentralized decision making and swarm intelligence.
*robustness : can be defined as the degree to which a system can still function in the presence of partial failures or other abnormal conditions.

1.4.2 Applications:

SR has not yet many real world applications that are already on the market because its relatively a new field of research. SR has a wide range of potential applications It is more preferable for the dangerous or inaccessible working area, tasks that requires a large area of space, scaling population, redundancy. Some domains of applications [60][61][62][63]:
-Arial and Aerospace technology:
for the arial: One of the most popular swarm robotics applications is the Unmanned Aerial Vehicles(UAVs), popularly known as “drones”. With swarm robotics, UAVs can flock and fly in formation without the need for a centralized control unit, even with a larger number of individuals. We can find a lot of researches about this from [64] and [65] to [66].

For aerospace: NASA developed Swarmies, small swarm robots, to collect samples like water, ice, and minerals on Mars for in-situ resource utilization (ISRU). They also launched a ”swarmathon” competition to encourage students to develop swarm algorithms inspired by ant foraging behavior. An experiment showed 20 Swarmies could travel 42 km in 8 hours, while the Mars rover Opportunity took 11 years to cover the same distance. Another NASA project aims to enhance Mars exploration using a swarm of robotic ”Marsbees” - flapping-wing flyers the size of bumblebees. Also A team of flying robot swarm may repair satellite or aircraft and Environmental swarm robots can maintain pipe inspection and pest eradication and Industrial robots could perform waste disposal and micro cleaning.
-industry 4.0 : Swarm robotics techniques have generated economic interest for strategic applications like agriculture and Industry 4.0 manufacturing. In Industry 4.0, swarm robots can enable smart warehouses, optimize machine scheduling, and more.Researchers have developed swarm robot platforms to prototype Industry 4.0 communication and behaviors. For example, Limeira et al. created Wi-Fi connected robots to test swarm communication for industrial tasks.Other projects apply swarm robots to warehouse management using cloud and local control. Simulation tools have been built to evaluate swarms for logistics like collision avoidance, path planning, and task scheduling specifically for warehouses. Swarm robot testbeds also aim to demonstrate cooperative payload transportation exceeding individual robot capacity. Through self-organization, simple robots can form formations to achieve collective goals in industry.
-farming : Swarm robotics also has promising applications in agriculture for tasks like inspection, mapping, seeding, harvesting, and plant care. For example, researchers have proposed using UAV swarms with computer vision to monitor crops and identify weeds autonomously. Test results indicate the feasibility of this approach. Studies have explored swarm robots for efficient crop inspection, comparing different UAV models. Minimalist swarm robots have been developed for seeding fields, with cloud connectivity and centralized intelligence. A novel swarm system architecture has been proposed for decentralized, flexible, and robust cereal harvesting.
-civil construction : Swarm robotics also has applications in construction, using mobile robots and modular building materials. Research has focused more on construction approaches rather than completing predefined structures. Robots like Romu use vibration and weight to automatically place posts and beams on the ground. This allows constructing flood barriers and other simple structures. Simulations examine using robot swarms over large areas with reactive algorithms to dynamically position barriers. Other projects study decentralized swarms that can expand 2D framework structures. Using force feedback, the robots can detect and prevent structural failures. The swarm builds any stable structure rather than following a set blueprint. Accessing local force data enables robots to build much larger unsupported cantilevers by maintaining force and stability. This allows construction in varied terrain.

-Military:
In Air Force:
Skyborg program: envisions autonomous wingmen flying alongside piloted fighter aircraft.
Perdix program: focused on swarms of low-cost micro air vehicles (MAVs) with approximately 12-in. wingspan (300 mm).
In Army:
DARPA project:
SquadX program: seeks to develop heterogeneous robot technology to work alongside dismounted infantry units to achieve significant advantages over adversaries.
OFFensive Swarm-Enabled Tactics (OFFSET) program: seeks insights into tactics for small ground military units accompanied by heterogeneous mixed air and ground swarms of over 250 autonomous assets.
In Navy:
Low-Cost Unmanned Aerial Vehicle Swarming Technology (LOCUST) program: developed swarms of dozens of small, low-cost UAVs, deployed from specialized canon-like launchers at a rate up to 1 drone every 1.33 s.
Autonomous mine countermeasures: detect and destroy underwater mines, a dangerous task currently undertaken by manned vessels and human divers.[67]
-education : in their research paper johal et al.[68] reviews published scientific literature on the use of swarm robots for education purposes in the last ten years, they find that the field is not so developed and its steal at its infancy, and a very few research actually implemented a user experiment with the goal to test their platform in educational settings and to demonstrate learning outcomes. The paper cited some used SR in the educational field like Cellulo [69] (activities: Windfield Study, Handwriting, Shapes, Symmetry); Micromvp (activities: Child-Robot Theater); Thymio (activities: House-Hunting Bees); zooids(activities: physical game); MSN(activities: Dice-puching); PSI(activities: programming).

1.5 Thesis objectives and methodology:

1.5.1 Identifying the methodology:

most studies in SR field are limited to VR simulations. Hence the principles of SR are rarely applied to real world problems [70]. Thus how Olaronke et al introduces the problem of using the empirical methodology in the SR field, and this can be easily observed with a small induction through the published research papers. Johal et al[71] they give the same remark said :" Our first remark after performing the data collection of papers and the filtering to empirically evaluated learning scenario, is that the field is not so developed…….very few research actually implemented a user experiment with the goal to test their platform in educational settings and to demonstrate learning outcomes". And thus because of the advantages that the simulation gives comparing with the design, creation and testing the nature-inspired algorithms on a real swarm of robots which is expensive and time consuming and may not lead to the desired or predicted results. In their paper "Fast, low-cost swarm robotics" Bartmess et al [72] estimate the cost of design and creation of 16 SR to be: 31,645.03$ for both the SR parts and the labor so that the cost of labor comes out to 31,000$ and the parts would be would be 645.03$.

1.5.2 The possible methodologies we can use in an SR thesis :

- Experimental: we could design and create a physical swarm robotics system to test it in order to evaluate different algorithms and parameters like in this paper [73].
- Simulation: is the Use a SR simulator like ARGoS, SwarmSimX.. etc. to test the algorithms and applications pf SR without building a real one like in this paper [74].
- Algorithm Development: create or develop new algorithms for swarm coordination and intelligence like in this paper [75].
- Modeling and Analysis: is about Developing a computational /mathematical models representing that mimic nature swarm and test it using simulations like in this paper [76].
- Case Study: Examine a real-world implementation of an SR as an example application like in this paper [77].
- Literature Review: survey prior SR research on a specific problem or application like in this paper[78].
- Hybrid: is a combination of two or more method from the methods cited above like in this paper [79]. For our work and due to the limitations and problems we cited above the methodology will be used in this thesis is "Hybrid" it is going to be:

The used methodology = Experimental + Simulation + literature review.

1.5.3 Thesis Objectives:

1. the thesis aims to apply a meta literature review and a systematic literature review methodology about the soft/hardware used create SR.

2. the thesis aims to apply Simulation methodology to test master-slave algorithm and follow the leader algorithm.

3. the thesis aims to apply Experimental methodology by building two SR that use master-slave algorithm.

Chapter 2

Meta Literature Review

The first method to be adopted in this thesis is the literature review method, literature review is “the collection of existing documents (both published and unpublished) on the topic, which comprise information, ideas, data and evidence written from a specific standpoint to fulfill certain aims or to express certain views on the nature of the topic and how it is to be examined, and the effective evolution of these documents in relation to the research being proposed”[80] it is a comprehensive overview about a targeting topic, it plays a foundational role in scientific research; they support knowledge advancement by collecting, describing, analyzing, and integrating large bodies of information and data[81]. We can resume the importance of LR in those few points that extracted from the paper of Andrew S. Denney and Richard Tewksbury[82]: learning: Literature reviews oblige the writer to learn nearly everything through the required research to write a LR. Credibility: Demonstrates the author’s expertise and establishes the credibility of the work’s argument. Identification of weaknesses: recognize the gaps in previous research, highlighting the need for further investigation. Argument formation: Helps the writer formulate a strong argument for why their research is necessary. Foreshadowing: Provides a foundation for the writer’s own study by reviewing and synthesizing prior literature. there are two main types of literature reviews, “traditional reviews are exploring issues, developing ideas, identifying research gaps, whereas systematic reviews are compiling evidence to answer a specific research or policy problem or question, using a protocol.”[83] in this work conducting a systematic review is better because, “it provides a systematic, transparent means for gathering, synthesising and appraising the findings of studies on a particular topic or question. The aim is to minimise the bias associated with single studies and non systematic reviews.”[83] and because that it is based on transparency and it is well structured it “renders itself amenable for replication.”[84] but first let’s take a look on the previous literature reviews on swarm robotics to both learning better how to write a LR and evaluate the reviews and compare it with this review.

2.1 A Literature Review Of Literature Reviews (Meta-literature review):

This meta-LR aims to present the reviews of last six years (2019-2024) on SR and its applications, using the traditional review methodology so it does not follow a rigorous and systematic methodology. It's starts by introducing the work of previous literature reviews then discussion it then identifying the gaps in the previous reviews and provide a criticism of them and the last thing is to Highlight the contributions of the literature review and its implications for future research. Swarm robotics is a relatively new field, but it has already shown great promise for a variety of applications, such as search and rescue, environmental monitoring, and manufacturing, those applications can't be realized or achieved without the existence of the bio-inspired swarm intelligence algorithms which are one of seven subcategories of the bio-inspired AI [85], It is mainly inspired from the social insects [86][87][88]and generally from social animals[89] in there behaviors specially like Foraging[90], flocking[91], aggregation[92] and stigmergy[93]. The definition of SR and some other concepts Its already mentioned above in the introduction, so its better to move now straight forward to talk about the published review papers on SR. the published papers some of them are conducted using traditional review and the other ones using the systematic review. Each of which discuss the subject of SR within a specific scope. According to ismail and hamami [94] the rate of publications on SR increased from 5 papers per year between 2011-2015 to nearly 20 paper per year between 2016-2020. This scientific papers differs, some of it are making a review about swarm robotics strategies and its applications in some domains like ismail and hamami [95] and Udugama [96] and Krishnamohan [97] and pradhan et al[98] and nedjah and junior [99], others about swarm intelligence like bahel et al [100] and Takeshi kano [101] and Prabhudesai [102] and odili et al [103], others about swarm robotics trends like Kuckling [104] and Diaz et al[87], others about a specific type of SR like jiang and renner [105] about underwater SR and Kabir et al[106] about molecular SR and abdelkader et al about Aerial SR[107] and johal et al [108] about educational SR, others are about SR from engineering perspective like Brambilla et al [109], others about a general review on SR like dorigo et al [110] and olaronke et al [111], others are about the simulatos and the platforms used in the research on SR like calderon-arc et al [112].

2.1.1 Meta-review about swarm intelligence

There are four choosing papers to be reviewed about SI, the 1st one was conducted by bahel et al, the authors showed the difference between the regular robots and swarm robots and the characteristics of SR, then the Architecture of SRs and theire comunication model, the paper introduce also SI applications in Search and Rescue, Defence, Space Science and Medicine. Finally they concluded that a lot of complex problems can be solved using SR which is a combinition of hard/soft ware technologies and bio inspired SI algorithms. The 2 nd one was conducted by Takeshi kano, the author starts his review by introducing the concept of SI using a Japanese proverb that says, “when three people gather together, they would have wisdom.” Thats mean that the individual robbot can not solve complex problems but a swarm of it can easly do that and the wisdom of people become the intelligence of the swarm. SI is an Interdisciplinary field starts whith (1) Understanding the mechanisms of real-world swarm phenomena, then (2) Designing artificial swarm intelligence systems. The paper emphasizes the importance of interdisciplinary collaboration between biologists, mathematicians, engineers, and other specialists to advance the understanding and application of swarm intelligence. Also the auther talks about the design of artificial intelligent systems using two approaches by Rule-Based Approach and Task-Based Approach. The 3rd Review was conducted by Prabhudesai, it is a comprehensive review of the state-of-the-art in swarm robotics, focusing on how it draws inspiration from the collective intelligence of social insects. The review discusses the key principles observed in social insect colonies, such as self-organization, decentralized decision-making, division of labor, communication, and adaptability. The auther also introduce the most influential and novel algorithms used in swarm robotics, including those for swarm aggregation, pattern formation, exploration, foraging, and obstacle avoidance. It is also discusses the importance of selecting appropriate sensors and hardware to enable effective communication, coordination, and collaboration among robots within a swarm. The 4th Review was conducted by odili et al, provides a comprehensive review of four recently developed swarm intelligence optimization algorithms : Cuckoo Search “CS”, Bat Algorithm “BA”, Teaching Learning-Based Optimization “TLBO”, and Jaya Algorithm “JA”. After they introduce the concept of SI, the authors present the four algorithms in detail starting with CS Algorithm that inspired by the brood parasitism of some cuckoo species, where cuckoos lay their eggs in the nests of other birds. It uses Lévy flights for exploration and has parameters like the number of nests and probability of cuckoo egg discovery it has been successfully applied to various optimization problems but can suffer from slow convergence speed and local optima issues. Then BA Algorithm which is inspired by the echolocation behavior of microbats it provides quick convergence in the initial stages but can suffer from premature convergence if the exploration-exploitation balance is not properly maintained. Another one is TLBO Algorithm, it is a parameter-less algorithm that simulates the teaching-learning process in a classroom, it have has two phases: the Teacher phase (exploration) and the Learner phase (exploitation), The algorithm has been widely applied but can suffer from premature convergence in complex problems and relatively slow speed. The last algorithm is JA algorithm is also a parameter-less algorithm and its more simple because it doesn’t require parameters tuning. Nevertheless the controlling of the algorithm-specific parameters in each iteration can be challenging, and its application is not yet as widespread as the other algorithms. Discussion: This set of review papers provides a comprehensive overview of SI in general and then it differs some of it illustrate the Interdisciplinary nature of the SI that requires an understanding of the source of insparation then exploit it in the domain of application like in kino's paper. In bahel's paper they additionally to the general idea of SI they talked about its application in various fields to solve complex problems. Odili's paper in the other hand concentrate on introducing four SI algorithms in detail. But Prabhudesai discusses the key principles observed in social insect colonies.

2.1.2 Meta-reviews about swarm robotics trends

Two choosing papers to be reviewed about this subject, the 1st one was conducted by Kuckling provides a comprehensive and insightful exploration of automatic design methods for swarm robotics, focusing on the application of robot learning and evolution. It effectively addresses the challenges of designing control software for decentralized, self-organizing robot swarms and presents a clear vision for future research directions. The 2nd review was conducted by Diaz et al. provides a comprehensive and updated overview of the SR field, covering its inspirations, definitions, key features, platforms, simulators, basic behaviors and tasks, and real-world applications. The authors have included recent advancements and developments in the field, making the review relevant and informative. They have also included recent advancements and developments in the field, making the review relevant and informative. Discussion: Both papers offer valuable insights into the field of SR, but they approach the topic from different angles and with varying levels of detail. Both papers cover fundamental SR concepts like self-organization, decentralization, and collective behavior also they talk about the natural inspiration of SR, Both reviews discuss essential SR behaviors such as aggregation. Both papers recognize the potential of SR in real-world scenarios, highlighting also examples about that. But The 2nd paper briefly mentions different design approaches like stigmergy and reinforcement learning. The 1st paper provides a detailed analysis of various automatic design methods, including neuro-evolution, automatic modular design, embodied evolution, and imitation learning.

2.1.3 Meta-reviews about a specific type of SR

Four choosing papers to be reviewed about this subject, the 1st one was conducted by jiang and renner providing a comprehensive overview of low-cost underwater swarm acoustic localization systems, focusing on recent research and field experiments. The paper highlights the increasing use of UUV swarms for various applications due to their affordability and ease of deployment. But of course it there are some challanges like the limitations of GNSS underwater necessitate alternative localization methods like acoustic, optical, and dead-reckoning techniques. also propagation delay, multipath interference, and high power consumption. The 2nd one was conducted by Kabir et al

This review article explores the exciting field of molecular SR, focusing on the use of bio- and nanotechnology to control large numbers of microscopic robots for complex tasks. The paper aptly showcases how biological components like biomolecular motors and DNA, along with nanotechnology tools, play crucial roles in constructing and controlling molecular robots. It describes also how DNA-based computation allows for implementing logic gates (YES, AND, OR) using swarm formation as the output, paving the way for more complex molecular computing systems. The 3rd one was conducted by abdelkader et al This paper explores the growing field of Aerial swarms, focusing on their applications and the technical challenges that need to be addressed for wider real-world adoption. The paper discusses various methods for localization and path planning highlighting the trade-offs and suitability of each approach depending on the specific application and environment. The 4th one was conducted by johal et al The authors conducted a systematic literature review using Google Scholar, searching for papers published between 2010-2020 that involve the use of swarm robotics in education. All the papers featured mobile robot swarms that moved on 2D surfaces like tabletops or the floor, Six different types of swarm robots were used, including Cellulo, Micromvp, Thymio, Zooids, MSN, and Psi. Children interacted with the swarm robots through various modalities like touch, GUI, and visual/force feedback. Most studies reported positive acceptability from participants, but did not demonstrate clear learning gains compared to other instructional methods. Discussion: all those papers are providing a comprehensive LR about four types of SR underwater, Aerial, Educational, molecular. The authors introduce the current state-of-the-art and key challenges across different domains of swarm robotics - underwater, molecular, aerial, and educational. They collectively highlight the growing interest and technical advancements in this field, as well as the significant hurdles that need to be overcome for wider real-world adoption and impact.

2.1.4 Meta-reviews about SR from engineering perspective

One choosing paper to be reviewed about this subject, Brambilla et al's paper provides a comprehensive overview of swarm robotics, specifically focusing on its potential for real-world applications through the lens of swarm engineering. The paper classifies this swarm engineering methods into two categories: Behavior-based design and Automatic design methods. paper remains a valuable and informative resource for understanding the fundamentals of swarm robotics and the principles of swarm engineering. However, considering the rapid advancements in the field, it would be beneficial to complement it with more recent research and discussions on real-world applications, hardware considerations, and ethical implications.

2.1.5 Meta-reviews about the general review papers on SR

Two choosing papers to be reviewed about this subject, the 1st one was conducted by dorigo et al provides a comprehensive overview of swarm robotics, exploring its history, current state, and potential future directions. They talked about the history of SR from the source of inspiration to the domain of application. Then they introduce the Lessons Learned from all this years of researches like: -Limited Robot Capabilities: The complexity of swarm robotics research is constrained by the capabilities of current robots, hindering large-scale experiments and real-world applications. Need for Shared Tools and Platforms: The research community would benefit from standardized robot platforms, simulators, and benchmarks to facilitate collaboration and progress. Micro-Macro Problem: Designing swarm behavior (macro-level) by programming individual robots (micro-level) remains a significant challenge, requiring more robust and scalable design methodologies. the 2nd one was conducted by presents a comprehensive overview of swarm robotics, exploring its inspiration, properties, applications, challenges, and future directions. Starting with the Inspiration and Definition, then the Key properties (Robustness, autonomy, scalability, homogeneity, local communication) Swarm behaviors: Aggregation, dispersion, safe-wandering, self-organization/assembly. Swarm robots offer advantages over individual robots in terms of speed, cost, robustness, reliability, and scalability and because of that SR needed to solve a lot of complex problems in real life applications medicine, agriculture, search and rescue, oil spill cleaning, exploration, and military operations. After the authors present the challenges like: Security concerns, Limited local communication capabilities can lead to deadlocks, Unreliable communication due to low-power sources, Uncertainty about the intentions of other robots can lead to competition instead of cooperation. Discussion: The 2nd paper provides a broader overview of the field, covering various aspects such as task allocation, human-swarm interaction, and information exchange. It systematically reviews existing literature to present a comprehensive picture of swarm robotics. It also provides a solid foundation for understanding the current state of swarm robotics research, including its applications and limitations. The 1st focuses on the historical development of swarm robotics, lessons learned, and future research directions. It delves deeper into specific topics like hardware miniaturization, heterogeneity in swarms, and the role of machine learning. Also builds upon this foundation by offering insights into how the field is evolving and where it might be headed in the future.

2.1.6 Meta-reviews about the simulatos and the platforms used in research on SR

one choosing paper to be reviewed about this subject, it was conducted calderon-arc et al. provides a comprehensive overview of swarm robotics, covering its conceptual foundations, simulation tools, real-life robot platforms, and applications. The paper clearly defines swarm robotics as the intersection of Swarm Intelligence SI and Multi-Robotics Systems MRS. The paper manifest clearly the importance of simulation as a too that play a crucial role in swarm robotics research, allowing for efficient testing and refinement of algorithms and robot designs before real-world deployment. The review presents a comprehensive list of commonly used simulation platforms like: Stage, Bio-pepa, team-bots, swarm-bots, ARGoS...etc. It showcases several prominent robots used in swarm research including: Epuck, kilobot, colias, Mona, PSI-swarm, Thymio. It also mentions the the applications like: navigation, Foraging, Exploration, Aggregation.

2.2 Identifying the gaps

It is rarely to see a paper without important gaps to be investigate and those paper that has been reviewed here are good reviews in general but there are some limitations that can be cited: Talking about the 1st set of papers about SR strategies we can see that there is a lack of investigation of those strategies in dynamic environments and the adaptation of those strategies in real-world. Also the Limited Exploration of Hybrid Approaches. The papers doesn't explicitly address the energy consumption of different consensus strategies or their scalability to larger swarms. As swarm robotics applications grow in scale and complexity, it becomes increasingly important to consider the energy efficiency of consensus algorithms and their ability to maintain performance with increasing numbers of robots. The 2nd set of papers about SI While the three papers provide comprehensive overviews of swarm intelligence, some potential gaps and areas for further exploration can be identified: Limited discussion of learning and adaptation: While the paper mentions adaptation, it doesn't deeply explore how swarm robotic systems can learn and evolve over time to improve their performance and handle novel situations. Lack of emphasis on human-swarm interaction: The paper focuses primarily on autonomous swarm behaviors without discussing the potential for human-swarm collaboration. Lack of focus on theoretical foundations: The paper primarily discusses existing research and applications without providing a strong theoretical framework to guide the design and analysis of swarm intelligence systems. Also ther is a small mistake in the paper of odili et al here :" while two of the algorithms: CS and TLBO are parameterized algorithms, the other two: TLBO and Jaya Algorithm are parameter-less." They mentioned TLBO algorithm twice, with the parameter and parameter-less algorithms the correct phrase will be :" while two of the algorithms: CS and BA are parameterized algorithms, the other two: TLBO and Jaya Algorithm are parameter-less."

The 3rd set of papers about swarm robotics trends While both papers provide a comprehensive overview of Swarm Robotics, some gaps can be identified: Software Architecture Considerations: The overview of swarm robotic projects briefly mentions software architectures but could benefit from a more detailed analysis of different architectural patterns and their suitability for various tasks and applications. Evaluation Metrics: The paper discusses the challenges of designing objective functions and reward functions but could benefit from a more thorough exploration of evaluation metrics for swarm performance, including task-specific and general metrics for efficiency, robustness, and adaptability.

The 4th set of papers about a specific type of SR, some gaps can be identified Jianng & renner's paper and abdelkade et al paper have a lack of detailed case studies of how low-cost swarm localization and aerial swarms can be applied to specific real-world problems. In Kabir et al paper The potential environmental impact of deploying large numbers of molecular robots is not discussed. However johal et al's paper primarily focuses on the acceptability of swarm robots in educational settings, lacking a deeper analysis of the actual learning outcomes and their comparison with traditional teaching methods.

2.3 Conclusion

This Meta-LR covered a wide range of conducted Reviews on SR in different subjects like underscoring the interdisciplinary nature of swarm robotics and the pivotal role of collaboration among researchers from various domains. The papers collectively highlight the significance of understanding the biological inspirations behind swarm behaviors and leveraging this knowledge to design robust, adaptable, and scalable robotic systems. Moreover, it shed light on key challenges facing the field, such as the need for standardization, energy efficiency considerations, and the development of appropriate evaluation metrics. While significant progress has been made in algorithm development and experimental validation, there remain important gaps to be addressed, particularly in dynamic environments, human-swarm interaction, and theoretical foundations. Finally , this meta-review not only illuminates the current state of the art in swarm robotics but also underscores the need for continued collaboration, innovation, and standardization to realize the full potential of swarm intelligence in addressing real-world challenges and advancing technological frontiers.

Chapter 3

A Systematic Literature Review On the used hardware and software in the design and creation of SR

After the conduction of the Meta-LR, we move forward to the SLR illustrating the hard/software needed to create a SR. the review will be systematic following a rigorous process mentioned in this book [113]

3.1 Brief Introduction

Every technology relies on a foundation of hardware and software for successful realization. Similarly, SR technology is built upon hardware and software inspired by natural SI algorithms. These algorithms, known as meta-heuristic algorithms, are used to solve optimization problems; a meta-heuristic is an "iterative generation process which guides a subordinate heuristic by combining intelligently different concepts to explore the search spaces using learning strategies in order to find efficiently near-optimal solution." [114] it is formed from two Greek words meta and heuristic, the concept coined by glover 1986.[115] as it is already mentioned m-h algorithms that used to solve optimization problems which are problems that "ask for minimal or maximal values of an objective function on a given domain." [116]te But for the hardware it's kind of complicated there is no standard hardware architecture for SR because there are a lot of types of SR (it is mentioned in the meta-LR) SR hardware in general refers to the physical components or devices used in the implementation of swarm robotics systems. These components can include sensors, actuators, processors, communication modules, power sources, and mechanical structures. The purpose of both hard/soft ware of SR is to build robots that can mimic the swarm behavior of social animals so the robots need to have Swarm characteristics which are Robustness, Flexibility, Scalability, decentralized, autonomous [117][118][119].

3.2 SLR Protocol

3.2.1 Research questions:

>what are the hardware components that SR should equipped with?
>What are the software that SR should come with?
>What are the future explorations of SR with identifying the gaps in the rviewed papers?

3.2.2 Exclusion Inclusion Criteria:

> The papers must be published between 2014-2024.
> The papers written in English.
> The papers are results of searching in google scholar, google search engine, semantic scholar.
> Exclude the duplicated papers that gives redundant information.
> The papers must be 4 pages or larger to avoid papers with lack of scientific methodology and details.
> Exclude the papers that are inaccessible.
> Exclude papers that do not contribute to the research after reviewing them.

3.2.3 Quality Criterion:

> Papers published in well-known scientific journals. > Papers that conducted in accordance with robust scientific methodology. > Significance and innovative contributions of the research study.

3.2.4 Execution:

The choice of the keywords was based on the subject, it was performed on the titles and those keywords are: In google scholar and semantic scholar those keywords was used: (swarm and (robot or robots or robotics) and (design or hardware or software)) + how to create a SR. In google search engine: hardware design implementation of swarm robot.
The result are:
99 paper –> google scholar.
72 paper –> semantic scholar.
25 paper –> google search engine.
196 paper–> in total.
After conducting the criteria cited above, it turned out to be 47 paper from 196 that meets the mentioned criteria which is 23.98% of the total number. Those 47 paper

subject distributed as follows:

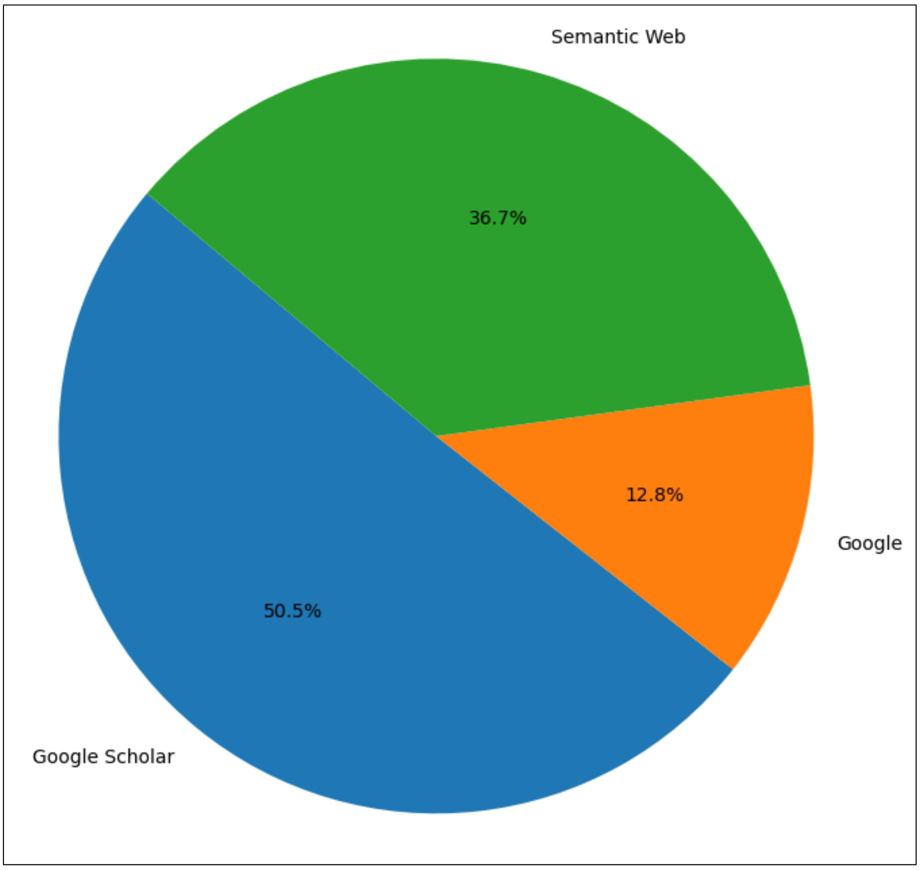

Figure 3.1: Distribution of Scientific Papers Across Different Search Engines

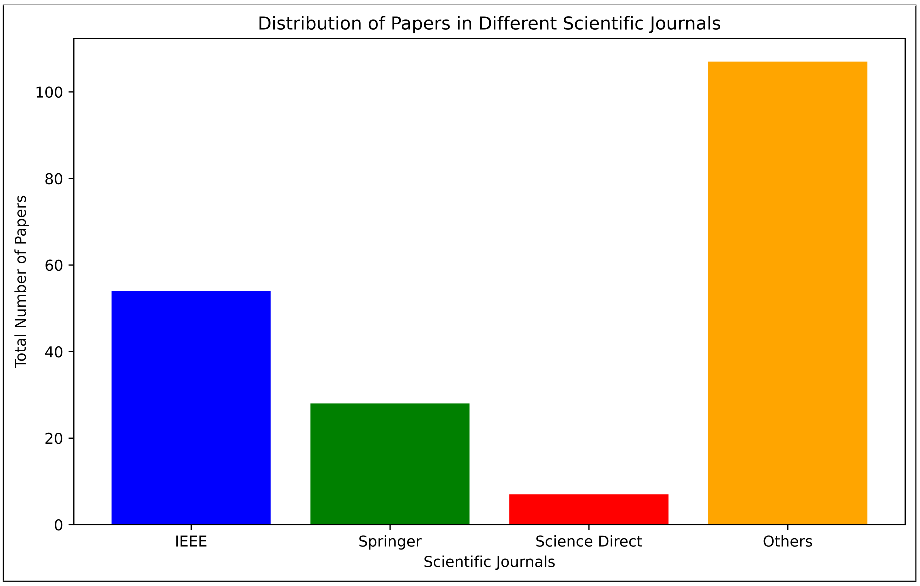

Figure 3.2: Distribution of Scientific Papers in regarding the scientific journals

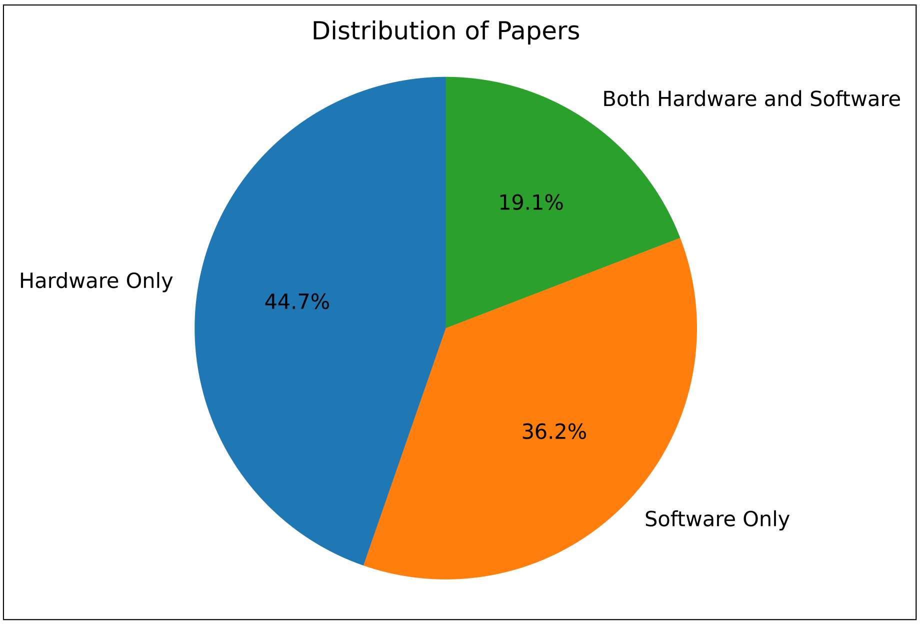

Figure 3.3: Distribution of Scientific Papers in regarding the subject

Before we start, it is worthy to notify that SR field is in need for an "urgent standardization in many aspects including the robots hardware and software" as nedjah and junior said [120] and this lack of standardization according to them is the one of the main reasons that SR applications are not yet in our daily life. The goal is to design of a swarm robots of really low cost yet easy to control their cooperation as to yield intelligent collective behaviors, there are there are attempts to solve the problems that are facing the standardization but they are ad-hoc. Each SR model is equipped with its own array of sensors, programming language, actuators.... This diversity complicates the migration of a project from one platform to another due to hardware and/or software incompatibilities. the goal of unification is still so far to accomplish it. However, there are some promising attempts like Villemure et al [121] hard/software open platform for SR development. The process of building SR divided into two parts: the hardware design and the software design.

3.3 The Hardware Design

The software acts as the intelligent core, providing a virtual environment that governs the robot's operations. It is the hardware that executes the instructions dictated by the software, translating them into physical actions. The problem regarding hardware is there is a lot of hardware variation depending on the environment (air(aerial SR), land(normal SR), sea(underwater SR)), The hardware variations in swarm robots are also driven by the specific requirements of the task as the experimental results of salman et al says[122], for example Cameras and vision sensors is more compatible with navigation tasks, Infrared or thermal sensors for rescue operations, Chemical sensors for environmental monitoring...etc. Also building SR under economical constraint is not like building it without those constraints because hardwares price differs, also the hardware differs from homogenouse SR to heterogenous SR[123] . In their work salman et al [124] The hardware specifications of each individual robot, the design of the control software orchestrating their behavior, and the optimal swarm size are heavily contingent upon the distinctive nature of the collective mission at hand, as well as the economic constraints and budgetary limitations imposed on the endeavor. However there is a general design that we can consider it as the basic design of all the SR:

1- Actuators and locomotion mechanisms:

- Aerial mechanism for aerial surveillance.
- Aquatic or underwater robots for marine applications.
- Legged robots for uneven terrain.
- Wheeled robots for flat environments.

2- Sensing:

- Cameras sensors for navigation, object recognition, or mapping.
- Infrared or thermal sensors for search and rescue operations.
- Chemical sensors for environmental monitoring or hazardous material detection.
- Sonar or radar sensors for obstacle avoidance or target tracking.

3- Communication and networking:

- WI-FI.
- Bluetooth.

- ZigBee.

- RFID.

4- Power supply:

- Lithium batteries.

- Solar panels.

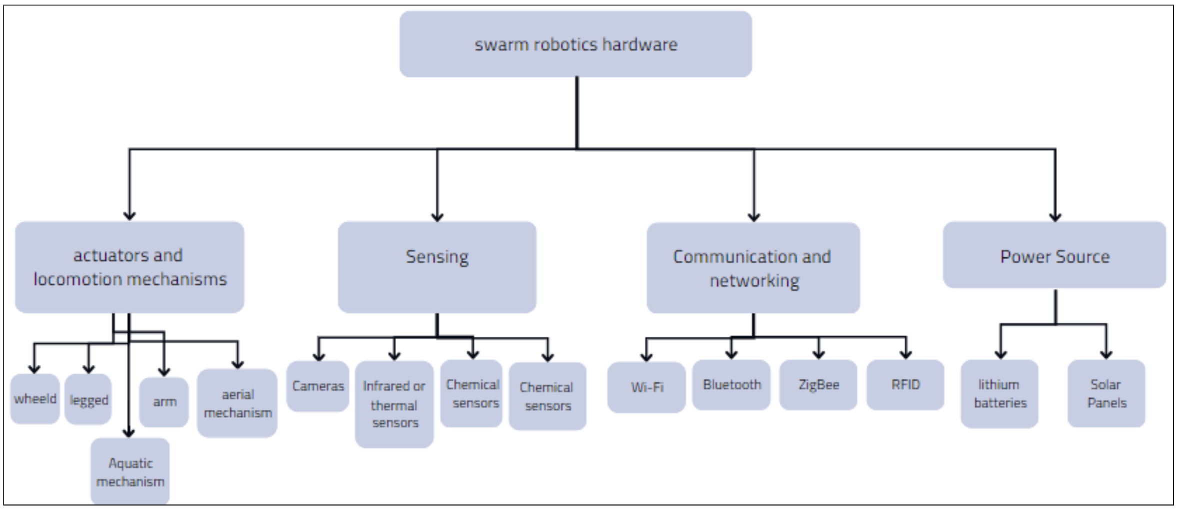

Figure 3.4: General hardware structure of swarm robotics

So “a universal swarm design methodology does not exist”[125], but a general hardware architecture that can be found in nearly each SR exists :

3.3.1 Sensors

The sensory unit used by the SR to perceive “the surrounding environment to the controller—a process known as mapping” [126] it is important for accomplishing the tasks such as detect and avoid obstacles, detecting its neighboring, and navigation, it is also used to collect sensory data that allows the SR to make decisions, each SR could be equipped with various sensors such as: cameras, Proximity and Range Sensors, GPS, humidity sensors, Temperature senors, chemichal sensors ... etc. Variations in the robotic sensors can cause the robot to perceive different informations, then Based on the varied sensory information, the robotic control unit generates distinct actuation directives for the actuators[127]. IR proximity sensor is the most commonly used sensor as it is small, easy to mount, and can detect objects at short ranges of 5-15 cm depending on the object's color[126], nedjah and junior say that IR is present in most of robots[128], it works by emitting infrared light which gets reflected off objects, with closer objects causing stronger reflection intensity. Reviewing the SR hardware papers (2014-2024) we can see different sensors implemented in SR projects, in cellulo project The robots, equipped with a downward facing camera[129], UBswarm developed at the RISC lab, University of Bridgeport, they use ultrasonic as well as photoelectric (Infrared) proximity sensors [130], for the zooids SR A flexible electrode is wrapped inside the 3D printed enclosure to provide capacitive touch sensing capabilities. An integrated capacitive touch sensing circuit is included (AtmelAT42QT1070) to detect user's touch [131], sensors in aquatic SR has been represented by costa et al [132] they include various sensors in each robot, namely a GPS receiver, a digital compass unit, and a temperature sensor. The GPS receiver, a GlobalTop FGPMMOPA6H module, provides position updates with a 5 Hz frequency and interfaces with the Single Board Computer (SBC) via UART protocol. It is coupled with an active 26 dB gain GPS antenna for improved signal quality and positioning accuracy of ± 3 m. The digital compass unit, a STMicroelectronics LSM303D magnetometer, provides heading information by compensating for magnetic readings based on the robot's pose. Due to interference concerns, the magnetometer is placed in a secondary enclosure located in the prow of the vessel. Temperature information is obtained from both the onboard SBC temperature sensor and a Maxim DS18B20 sensor positioned in the vessel's bottom to measure water temperature. The DS18B20 sensor provides digital temperature readings with 12-bit resolution and interfaces with the SBC via One-Wire standard protocol. Bartmess et al [133] in their project to build Fast, Low-Cost Swarm Robots a webcam will be positioned above a table, facilitating the observation of the tabletop surface along with the robots situated on it. This webcam will establish a connection with the computer through a USB interface. Being an off-the-shelf component, it adheres to the cost constraints set for the vision system. The webcam will derive its power supply through the USB connection itself. In shang's phd thesis [127] he relies on two IR photoelectric sensors they are located at the front of the robot, The magnitude of the IR sensor output can therefore be obtained bysumming the response of individual reflective point within sensor's viewing range:

$$S(x, \theta) = \frac{\alpha}{x^2} \cos(\theta) \tag{3.1}$$

where: S(x) is the IR sensor's response to an individual reflective point.

θ is the incidence angle of the reflective light.

x is the distance between the sensor and the reflecting point on the ground.

v is the IR sensor's viewing angle.

α is the gain of the amplifier and determines the sensitivity of the sensor.

$$V_{\mathrm{IR}} = \sum_{n=1}^{n} S(x_n, \theta_n) + \beta \tag{3.2}$$

n is the number of dots within the IR sensor's viewing angle.

β models the sensor's output offset and the effect of ambient light.

In the Colias SR [134], only IR proximity sensors are used. The reflected IR value that is measured by a sensor is mathematically modeled by the following equation:

$$s(x, \theta) = \frac{\alpha_c \cos\theta}{x^2} + \beta_c \tag{3.3}$$

$s(x, \theta)$ sensor output.

x is the distance of the obstacle.

θ is the angle of incidence with the surface.

α_c includes several parameters such as the reflectivity coefficient, output power of emitted IR, and sensitivity of the sensor.

β_c is the offset value of the amplifier and the ambient light effect.

Another aquatic SR project "Jeff" by Mintchev et al [135] their AUV's equipped with a wide range of sensors and local communication systems. Underwater navigation relies on a pressure sensor to measure depth and a gyroscope. accelerometer and a magnetometer to control attitude and Locomotion, additional sensor payloads (e.g. temperature, concentration of chemicals, camera) that can be plugged into Jeff's shell. SwarmUS has been equipped with are equipped with a A2M8 RPLidar, D400 series Realsense Camera [121] In their project, Mustafa et al[136] utilize the HC-SR04 ultrasound sensor from ElecFreaks. Operating at 5V DC, it utilizes sonar to measure distances to objects. Each module comprises an ultrasonic transmitter, receiver, and control circuit, with pins for power, trigger (transmitter), echo (receiver), and ground. The sensor emits ultrasound pulses at a constant 40 kHz frequency, consisting of 8 cycles per burst. It captures echoes lasting milliseconds. With an accuracy range of about 3 mm and a pulse travel range of 2–500 cm, the sensor is utilized for collision avoidance with both static and dynamic objects, including other robots within a swarm, as well as the physical boundaries of the 3D environment. The 25g pico quadrotor with the protective cage is equipped with A wireless camera installed on the bottom of the pico quadrotor capable of real-time video feedback [137], another SR project is has been equipped with additional introspective sensors (specifically motor current and temperature sensors) [138], S-Bot robot has various sensors used for different application. three specific sensors: the ultrasonic distance sensor HCSR04, the sharp distance sensor 2Y0A21, and a general-purpose proximity sensor using IR emitter and receiver pair. The HCSR04 has a working range of 2cm to 400cm with an accuracy of 3mm, while the Sharp GP2Y0A21YK0F measures distances from 10 to 80 cm, with its output voltage corresponding to the detection distance. The general-purpose proximity sensor operates using IR emitter and receiver pair, with a range of 2cm to 15cm, adjustable via an onboard potentiometer. Additionally, it is noted for its compact design and low power consumption[139][140], also The Bulubot prototypes utilize two types of sensors. Firstly, the Sharp GP2Y0A41SK sensor, an infrared proximity short-range sensor, is employed for obstacle detection. Secondly, a 10 mm light-dependent resistor is utilized for light following[141], in bump sensors mounted facing upwards on the bottom circuit board. These sensors enable the detection of the direction of impact with an average error of 8.1°. The bump sensor is utilized for obstacle avoidance, estimation of the angle of impact [142], mROBerTO's have proximity-sensing module, and swarm-sensing module [143], in their work SR material handling and their applications on the conservation of solar energy kumar et al [144] the SR has been equipped with IR proximity Sensor, Temperature Sensor, Humidity Sensor and LDR. An IR sensor TSOP75436WTT is placed on the back of RiBot [145], HeRo [146]uses only IR proximity sensors to avoid obstacles as well collisions with other robots. The IR sensory system consists of three TCRT5000 long-range sensors Those sensors are placed in front of the robot and have a range of approximately 20 cm. Moving now to the simulation conducted by shang et al [147] Two downward pointing IR sensors are located at the front of the robot. For this project [148] a combination of switches and infrared sensors was chosen. The ATtiny85 has an ADC module that can read changes in voltage on some of the I/O pins we will use this ability to read the voltage from an IR receiver and define the robbots distance.

3.3.2 Actuators and locomotion mechanisms

as the muscels help in the movement and coordination of humans, actuators move or actuate the joints and links of the robot as per the signals given by the controller. the actuators help the robot to withstand the forces of gravity, inertia, and to work against the external forces while its operation.[149] in the work of Mustafa et al [136] The main components of their SR platform are the wheels and servomotors whereas the robot movement is provided through two side wheels with power supplied by two continuous rotation servomotors Unlike ordinary motors, servomotors can be individually controlled; they only require the angle of rotation for motion. Rotation is supported through an omni-directional ball caster wheel able to swivel in any direction. As for SwarmUs platform [121] it does not directly talk about actuators. Instead, it focuses on providing the coordination, communication, and localization features necessary for swarm behavior, however A Pioneer 2DX with a SwarmUS is mainly equipped with wheels. While Jeff the aquatic SR [135] utilizes a combination of DC motors and cleverly designed mechanisms to achieve control over its movement and buoyancy, making it a versatile platform for underwater swarm operations, with a Buoyancy System of One DC motor This motor controls the cam and piston mechanism, adjusting Jeff's buoyancy for up/down movement (heave) and depth control, and Docking System of One DC motor This motor controls the orientation of the magnet within the docking station, facilitating attraction and repulsion for docking and undocking procedures. Another aquatic SR actuators are represented in the work of costa et al [132] with Two DC motors are employed for propulsion, each driving a propeller through a shaft. The paper mentions two specific models used: NTM Prop Drive Series 28-30A 750 kv/ 140 w Emax 2215/25 950 kv 2-3S, and Electronic Speed Controllers (ESCs): These control the speed and direction of the DC motors, allowing for precise maneuvering of the robot. The specific ESC used is the HobbyKing 50 A Boat ESC 4 A UBEC. Colias [134] is propelled by two miniature DC motors that utilize direct gears and two wheels with a diameter of 2.2 cm, enabling it to attain a maximum speed of 35 cm/s. The rotational velocity of each motor is individually regulated through the employment of a pulse-width modulation (PWM) technique. Separate H-bridge DC motor drivers power each motor, with an average power consumption of 35 ± 5 mA under no-load conditions and up to 150 ± 20 mA when stalled. In their work to achieve the building of fast low-cost SR Batmess et al [133] use two DC motors per robot, responsible for propelling the robot around the table. 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In their review patil et al [126] they conclude regarding to the used actuators that DC Motors are Widely used for driving wheels and tracks in various swarm robot platforms including: E-puck, Alice, Sumobot, Swarm-Bot, AutoBot, CYBOTS and others, and Stepper Motors Offer precise control and are used in some platforms like E-puck and Nanokhod, and Servo Motors: Provide positional control and are often used for locomotion and other actuation tasks, also Piezoelectric Actuators: Utilized for locomotion and actuation in microrobots due to their small size and precision, Gear Motors: Used in some robots like TerminatorBot for more powerful manipulation.Spring Return Actuators: Employed in some robots for simple hook-based connection mechanisms, Solarbotics Motors: Featured in MiLy-Bot for their low power consumption and high torque. In his phd thesis, shang [150] uses DC motor and two wheels in his SR design. 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3.3.3 Communication And Networking

"In multi robot system for inter robot communication media is used to share information and make a collective decision."[139] Wireless communication is mostly used when a scenario is accomplished with mobile robots. [134] The choice of communication module depends on factors like[123]: Communication Distance Capability: The X-Bee modules have more extensive communication range in comparison to the Bluetooth Bee modules. Data Transmission Speed: The PmodWiFi module, when it mixed with the SPI interface, facilitates a higher rate of data transfer comparing to the X-Bee and Bluetooth Bee modules. Energy Consumption: Each module exhibits distinct power requirements. • Moustafa et al [136] in their hardware robotic platform they use a built-in communication interface for communications via Bluetooth 4.1 for very short distances (10 m or less), and an 802.11n wireless LAN for wider areas (100m), and an FM receiver operating in the 65-108 MHz FM bands. These wireless capabilities are enabled by the Cypress CYW43438 wireless chip. The various wireless communication options are utilized for facilitate short and long-range communication for the swarm robot system. SwarmUS has been equipped with communication system utilizes a Wi-Fi network for data exchange, with broadcast messages for updating shared information and unicast messages for sending commands. It employs a messaging system based on Protobuf and RPC mechanisms to route communications between agents, hosts, and other system components.[151] moving to the aquatic SR Jeff [135] is equipped with Blue LED units used for communication and distance sensing, each unit have two paires of LEDs, One pair with 1m range, 60° beam for communication, Another pair with 0.5m range, 120° beam for obstacle detection. 14 electrodes inspired by electrosensory capabilities of fish Enables communication and localization through electric field detection/interpretation with the Range of 250-500mm, more then that it is also have Two loudspeakers, one on each side with the Range of 0.5-1m, and finally a Microphone that Receives acoustic signals from a floating station Used for a virtual fence system to confine the swarm within a designated area. Colias [134] uses infrared (IR) technology for both communication and sensing, it utilizes short-range IR bump sensors for basic obstacle avoidance, while the long-range IR proximity sensors provide both environmental sensing capabilities (obstacle detection and range estimation) as well as a means for direct communication between robots in the swarm. Back to another aquatic SR developed by costa et al [132] is equipped with A TP-Link TL-WN722N Wi-Fi adapter with a high-gain antenna allows robots to communicate wirelessly with each other over a range of 40 meters on the water. The Fast, Low cost 16 SR developed by bartmess et al [133] is equipped with a Wi-Fi router capable of transmitting a 2.4GHz signal to the robots. The router will be communicating to the robots with a UDP connection to allow for quick and frequent connections. It will connect to the computer using an Ethernet cable it Connects to 16 devices at one time and Transmit 16 packets of 16kb in under 100ms. Zooids [131] are equipped with two main pieces of communication and networking hardware: 2.4GHz Radio Chip (Nordic nRF24L01+) Enables wireless communication between each Zooid and a master computer, it is Essential for receiving commands from the master, also Allows sending back information like position and touch sensor status to the master. The UB Robot Swarm[123] utilizes a variety of communication modules depending on the specific robot and its role within the swarm: X-Bee modules: These modules offer reliable wireless communication for both indoor and outdoor environments. They operate using serial communication (Tx/Rx) and are compatible with other modules like Bluetooth Bee.

Bluetooth Bee modules: Similar to X-Bee, these modules use serial communication and are well-suited for short-range communication within the swarm.'

PmodWiFi modules: This option provides wireless communication through WiFi connectivity. It utilizes the SPI mode for data transmission and reception, offering faster data rates compared to serial communication.

Cellulo SR project [129] use wireless RN-42 Bluetooth for communication. Patil et al in their review on SR hardware [126] they mentions various communication and networking options used in swarm robotics, each with its own advantages and drawbacks "Short-Range Communication" like Infrared (IR) transceivers/sensors it is Low cost, simple implementation, good for obstacle detection and short-range robot-to-robot communication but in the other hand it is Limited range, susceptible to interference from ambient light, requires line-of-sight. For Examples: SwarmBot, S-Bot, CONRO. Also Ultrasonic sensors which are Longer range than IR, can measure distance and angle, but it is Sensitive to object material and surface properties, less accurate than IR. For the Long-Range Communication another hardwares mentionned in the review like the Radio Frequency (RF) modules which is Longer range than IR or ultrasonic, good for complex environments, but the Potential interference from other RF devices, can be more expensive. Another one is bluetooth it is Relatively low cost, readily available modules, good for moderate data transfer but is short in its range then the (RF), and finally Wireless LAN (Wi-Fi) which is High bandwidth, good for large data transfers but it is Higher power consumption, potential interference issues, more expensive. in his thesis about Hardware Variation in Robotic Swarm [127], shang categorize the communication methods into three main types and provides examples of technologies used within each category:

1. Interaction via Communication: Short-range wireless transmission: This often involves the use of radio frequency (RF) modules like Zigbee or Bluetooth. Infrared (IR) broadcasting communication: IR transceivers enable robots to exchange information using infrared light. LEDs for information indication: Robots can use onboard LEDs to signal their state or other data to nearby robots.
2. Interaction via Sensing: Sonar: Ultrasonic sensors allow robots to detect the distance and direction of nearby robots without direct communication.
3. Interaction via the Environment: Virtual pheromones: This approach utilizes the environment to ”memorize” information, similar to how ants use pheromones. The actual implementation can vary, with examples including using wireless communication to maintain virtual pheromone information among robots.
The 25g swarm pico quadrotors [137] primarily use ZigBee communication modules for wireless communication. The Robotarium [138] primarily relies on WiFi (IEEE 802.11 B/G/N) for communication between the robots and the central server. Each GRITSBot is equipped with an ESP8266 chip that provides WiFi capabilities with a bandwidth of up to 54 MBit/s. The S-bot [139] use CC2500 Serial Communication Module for communication as shows in The CC2500 is a lowcost 2.4 GHz transceiver which is designed for very low-power wireless applications. The module is designed to work for the 2400-2483.5 MHz ISM (Industrial, Scientific and Medical) and SRD (Short Range Device) frequency band. CC2500 has RS232 UART interface with variable baud rate, Programmable Device Address (255 per channel) and Standard configuration baud rate of 9600. in Demir’s master thesis [141] The focus of his work is on the mechanical design, leg optimization, and individual robot control for achieving flocking behavior, so he doesn’t mention any communication hardware. in the r-one SR [142], Communication is handled by eight IR transmitters, eight IR receivers, a 2.4 GHz radio with 2Mbps data rate, and a USB port. To interact with the user, For user interaction, the robot incorporates a VLSI1053 audio chip capable of MIDI playback, accompanied by three push buttons and three separate arrays, each consisting of five LEDs emitting light. Another SR is mROBerTO [143], it is equipped with two types of communication hardware wireless RF “ANT™” for low-power mesh networking and “BLE” for higher bandwidth and an infrared multi-channel system for local robot-to-robot communication and relative positioning. This suite of hardware enables effective communication, networking and localization capabilities for the SR system. In their work kumar et al [144] primarily focuses on Bluetooth modules for communication between the swarm robots and potentially with a computer Each robot is equipped with a Bluetooth module, Utilizes serial communication mode (Tx and Rx) for data exchange, Enables decentralized communication among the robots. While HeRo [146] is equipped with a NodeMCU v3 board which has a built-in ESP8266 microprocessor that provides WiFi communication capabilities. This allows the robot to connect to a network and communicate with other devices, including a central computer running

the Robot Operating System (ROS). In Abuelhaija et al's [148] work the cmmunication of SR in this project rely on an indirect form of communication through infrared (IR) sensors, By measuring the strength of the received IR signal, a robot can estimate the distance to other robots within its line of sight. This information is then used by the control algorithm to guide the robot's movement and achieve swarming behavior.

3.3.4 Power Source

Power sources to a robot are like the engine to the car [152], so it is important to equip the SR with the right power source depending on factors like the size of the robot its mission...etc. moustafa et al [153] in their SR platform used a rechargeable power-efficient 3.7 V lithium-ion polymer battery, the system includes a boost converter to step up the battery voltage to the required level, and a specialized lithium battery charger module that provides charging/discharging management, temperature control, and various protection features to ensure safe and reliable operation of the battery power source. SwarmUS [121] equipped with 11.1 V LiPo battery A DC/DC converter is used to step down the robot's battery voltage to power the SwarmUS boards, and the Hiveboard distributes power to the connected Beeboards. about Jeff the aquatic SR is equipped with an 8 Li-Po cells with a capacity of 880 mAh each. Autonomy up to 120 minutes, energy is stored in a lithium battery pack located in Jeff's stern. it have also a Battery Status Monitoring Circuits Dedicated circuits monitor the battery's state of charge and remaining capacity. This information is crucial for Jeff's cognitive capabilities, allowing it to make informed decisions about energy usage and potentially seek recharging when needed. Another SR is Colias [134], utilizes A 3.7V, 600 mAh lithium-polymer battery serves as the primary power source. This battery is expandable up to 1200 mAh for increased autonomy, The lower board of the robot houses a dedicated power management system. This system monitors and controls the power consumption of various robot functions. The aquatic SR developed by costa et al [132] utilizes two LiPo batteries, one dedicated to powering the motors and propulsion, and the other for control, processing, and sensing components. The control battery is regulated by an SBEC to provide a stable 5V DC supply. For the Fast, Low cost 16 robots developed by Bartmess [133] they use Lithium-Ion Battery (500mAh), a circuit manages the charging process of the Li-Ion battery, preventing overcharging and undercharging to ensure safety and battery longevity, a Voltage Regulator (LDL1117S33R): This component regulates the voltage from the battery to a steady 3.3V, which is required for powering the ESP8285 SoC and other components. Each zooids robot SR [131] is powered by a 100 mAh LiPo battery, Most of the power in the robots are consumed by the motors, radio module, micro-controller, and LED. the zooids are capable of moving for one hour, and can work even longer under normal usage. UB Robot Swarm [123] are powered by NiMH or LiPo batteries, chosen for their size, weight, and power characteristics. Power distribution and management involve considering the current consumption of individual components, as well as environmental factors and operational patterns. the paper of the cellulo project [129] does not mentionned the details of the power supply of their SR but it is a rechargeabale battery because cellulo have a USB port for recharging it. In the Review paper about SR hardware[126] the authors mention several power supply like the Rechargeable lithium batteries which are the most prevalent choice due to high energy density, compact size, and light weight specialy Lithium-polymer (Li-Po) batteries which are favored for safety and thin profile, SR typically operate on a voltage range of 5V to 25V DC power. also they mention some factors that influencing battery choice:

-Robot size and weight: Smaller robots require smaller, lighter batteries.

-Power consumption: Robots with more sensors, actuators, and processing power need higher-capacity batteries.

-Mission duration: Longer missions necessitate batteries with longer run times.

The energy supply hardware used in the pico quadrotor described in the paper[137] is a 3.7V, 340mAh Lithium Polymer (LiPo) battery. the robotarium (GRITSbots) [138] uses 400 mAh LiPo

battery: This is the onboard energy storage for each robot, allowing them to operate for up to 40 minutes on a single charge, and a Wireless charging system. S-Bot [139] has 12 Volts rechargeable battery for powering of all system. Using external charger battery can be charged as and when required. the r-one robot [142] is equipped with the following energy supply hardware: 3.7V 2000mAh Lithium Polymer (LiPo) Battery, The robot can be charged via the USB port, An additional charging method is available through a docking connector. mROBerTO [143], utilizes the following energy supply hardware: Three 3.7V Li-Po batteries connected in parallel Voltage divider and ADC port for battery monitoring. In their survey about on swarm robotics material handling and their applications on the conservation of solar energy, Kumar et al [144] they pointed to Li-Po batteries as the primary power source, supplemented by miniature solar panels that harvest solar energy to recharge the batteries and extend their operational time. Additional hardware components like solar charge controllers and power meters are employed to manage and optimize energy usage and storage. The Ri-Bot [145] uses a small 40mAh rechargeable LiPo battery as its main power source. The battery can be conveniently recharged through contacts in the robot's "eyes" without needing to disassemble the device. With continuous tail movement, the battery provides around 23 minutes of runtime, while intermittent tail usage extends the operating time beyond 1 hour. The HeRo SR, is equipped with 3.7V 1000mAh Li-Po battery and 5V step-up boost converter this converter efficiently steps up the voltage from the 3.7V battery to the required 5V level. Finally the paper of abuelhaija et al [148], The paper describes their SR as being powered by Two rechargeable 4.2V lithium-ion batteries, One battery is dedicated to powering the motor circuit, while the other supplies energy to the control circuit, This separation is likely done to isolate potential electrical noise from the motors and ensure stable power delivery to the sensitive control electronics.

3.3.5 Actuators and locomotion mechanisms

as the muscels help in the movement and coordination of humans, actuators move or actuate the joints and links of the robot as per the signals given by the controller. the actuators help the robot to withstand the forces of gravity, inertia, and to work against the external forces while its operation.[149] in the work of Mustafa et al [136] The main components of their SR platform are the wheels and servomotors whereas the robot movement is provided through two side wheels with power supplied by two continuous rotation servomotors Unlike ordinary motors, servomotors can be individually controlled; they only require the angle of rotation for motion. Rotation is supported through an omni-directional ball caster wheel able to swivel in any direction. As for SwarmUs platform [121] it does not directly talk about actuators. Instead, it focuses on providing the coordination, communication, and localization features necessary for swarm behavior, however A Pioneer 2DX with a SwarmUS is mainly equipped with wheels. While Jeff the aquatic SR [135] utilizes a combination of DC motors and cleverly designed mechanisms to achieve control over its movement and buoyancy, making it a versatile platform for underwater swarm operations, with a Buoyancy System of One DC motor This motor controls the cam and piston mechanism, adjusting Jeff's buoyancy for up/down movement (heave) and depth control, and Docking System of One DC motor This motor controls the orientation of the magnet within the docking station, facilitating attraction and repulsion for docking and undocking procedures. Another aquatic SR actuators are represented in the work of costa et al [132] with Two DC motors are employed for propulsion, each driving a propeller through a shaft. The paper mentions two specific models used: NTM Prop Drive Series 28-30A 750 kv/ 140 w Emax 2215/25 950 kv 2-3S, and Electronic Speed Controllers (ESCs): These control the speed and direction of the DC motors, allowing for precise maneuvering of the robot. The specific ESC used is the HobbyKing 50 A Boat ESC 4 A UBEC. Colias [134] is propelled by two miniature DC motors that utilize direct gears and two wheels with a diameter of 2.2 cm, enabling it to attain a maximum speed of 35 cm/s. The rotational velocity of each motor is individually regulated through the employment of a pulse-width modulation (PWM) technique. Separate H-bridge DC motor drivers power each motor, with an average power consumption of 35$\pm$5 mA under no-load conditions and up to 150$\pm$20 mA when stalled. In their work to achieve the building of fast low-cost SR Batmess et al [133] use two DC motors per robot, responsible for propelling the robot around the table. These motors are likely connected to the wheels, allowing for differential drive (turning by varying the speed of each wheel), and Motor Controllers: The design incorporates motor controller ICs to interface with the DC motors. These controllers receive PWM signals from the SoC and translate them into appropriate signals for driving the motors, controlling speed and direction.

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1. Interaction via Communication: Short-range wireless transmission: This often involves the use of radio frequency (RF) modules like Zigbee or Bluetooth. Infrared (IR) broadcasting communication: IR transceivers enable robots to exchange information using infrared light. LEDs for information indication: Robots can use onboard LEDs to signal their state or other data to nearby robots.
2. Interaction via Sensing: Sonar: Ultrasonic sensors allow robots to detect the distance and direction of nearby robots without direct communication.
3. Interaction via the Environment: Virtual pheromones: This approach utilizes the environment to ”memorize” information, similar to how ants use pheromones. The actual implementation can vary, with examples including using wireless communication to maintain virtual pheromone information among robots.

The 25g swarm pico quadrotors [137] primarily use ZigBee communication modules for wireless communication. The Robotarium [138] primarily relies on WiFi (IEEE 802.11 B/G/N) for communication between the robots and the central server. Each GRITSBot is equipped with an ESP8266 chip that provides WiFi capabilities with a bandwidth of up to 54 MBit/s. The S-bot [139] use CC2500 Serial Communication Module for communication as shows in The CC2500 is a lowcost 2.4 GHz transceiver which is designed for very low-power wireless applications. The module is designed to work for the 2400-2483.5 MHz ISM (Industrial, Scientific and Medical) and SRD (Short Range Device) frequency band. CC2500 has RS232 UART interface with variable baud rate, Programmable Device Address (255 per channel) and Standard configuration baud rate of 9600. in Demir’s master thesis [141] The focus of his work is on the mechanical design, leg optimization, and individual robot control for achieving flocking behavior, so he doesn’t mention any communication hardware. in the r-one

SR [142], Communication is handled by eight IR transmitters, eight IR receivers, a 2.4 GHz radio with 2Mbps data rate, and a USB port. To interact with the user, For user interaction, the robot incorporates a VLSI1053 audio chip capable of MIDI playback, accompanied by three push buttons and three separate arrays, each consisting of five LEDs emitting light. Another SR is mROBerTO [143], it is equipped with two types of communication hardware wireless RF “ANT™” for low-power mesh networking and “BLE” for higher bandwidth and an infrared multi-channel system for local robot-to-robot communication and relative positioning. This suite of hardware enables effective communication, networking and localization capabilities for the SR system. In their work kumar et al [144] primarily focuses on Bluetooth modules for communication between the swarm robots and potentially with a computer Each robot is equipped with a Bluetooth module, Utilizes serial communication mode (Tx and Rx) for data exchange, Enables decentralized communication among the robots. While HeRo [146] is equipped with a NodeMCU v3 board which has a built-in ESP8266 microprocessor that provides WiFi communication capabilities. This allows the robot to connect to a network and communicate with other devices, including a central computer running the Robot Operating System (ROS). In Abuelhaija et al’s [148] work the cmmunication of SR in this project rely on an indirect form of communication through infrared (IR) sensors, By measuring the strength of the received IR signal, a robot can estimate the distance to other robots within its line of sight. This information is then used by the control algorithm to guide the robot’s movement and achieve swarming behavior.

3.3.7 Power Source

Power sources to a robot are like the engine to the car [152], so it is important to equip the SR with the right power source depending on factors like the size of the robot its mission…etc. moustafa et al [153] in their SR platform used a rechargeable power-efficient 3.7 V lithium-ion polymer battery, the system includes a boost converter to step up the battery voltage to the required level, and a specialized lithium battery charger module that provides charging/discharging management, temperature control, and various protection features to ensure safe and reliable operation of the battery power source. SwarmUS [121] equipped with 11.1 V LiPo battery A DC/DC converter is used to step down the robot’s battery voltage to power the SwarmUS boards, and the Hiveboard distributes power to the connected Beeboards. about Jeff the aquatic SR is equipped with an 8 Li-Po cells with a capacity of 880 mAh each. Autonomy up to 120 minutes, energy is stored in a lithium battery pack located in Jeff’s stern. it have also a Battery Status Monitoring Circuits Dedicated circuits monitor the battery’s state of charge and remaining capacity. This information is crucial for Jeff’s cognitive capabilities, allowing it to make informed decisions about energy usage and potentially seek recharging when needed. Another SR is Colias [134], utilizes A 3.7V, 600 mAh lithium-polymer battery serves as the primary power source. This

battery is expandable up to 1200 mAh for increased autonomy, The lower board of the robot houses a dedicated power management system. This system monitors and controls the power consumption of various robot functions. The aquatic SR developed by costa et al [132] utilizes two LiPo batteries, one dedicated to powering the motors and propulsion, and the other for control, processing, and sensing components. The control battery is regulated by an SBEC to provide a stable 5V DC supply. For the Fast, Low cost 16 robots developed by Bartmess [133] they use Lithium-Ion Battery (500mAh), a circuit manages the charging process of the Li-Ion battery, preventing overcharging and undercharging to ensure safety and battery longevity, a Voltage Regulator (LDL1117S33R): This component regulates the voltage from the battery to a steady 3.3V, which is required for powering the ESP8285 SoC and other components. Each zooids robot SR [131] is powered by a 100 mAh LiPo battery, Most of the power in the robots are consumed by the motors, radio module, micro-controller, and LED. the zooids are capable of moving for one hour, and can work even longer under normal usage. UB Robot Swarm [123] are powered by NiMH or LiPo batteries, chosen for their size, weight, and power characteristics. Power distribution and management involve considering the current consumption of individual components, as well as environmental factors and operational patterns. the paper of the cellulo project [129] does not mentionned the details of the power supply of their SR but it is a rechargeabale battery because cellulo have a USB port for recharging it. In the Review paper about SR hardware[126] the authors mention several power supply like the Rechargeable lithium batteries which are the most prevalent choice due to high energy density, compact size, and light weight specialy Lithium-polymer (Li-Po) batteries which are favored for safety and thin profile, SR typically operate on a voltage range of 5V to 25V DC power. also they mention some factors that influencing battery choice:
-Robot size and weight: Smaller robots require smaller, lighter batteries.
-Power consumption: Robots with more sensors, actuators, and processing power need higher-capacity batteries.
-Mission duration: Longer missions necessitate batteries with longer run times.
The energy supply hardware used in the pico quadrotor described in the paper[137] is a 3.7V, 340mAh Lithium Polymer (LiPo) battery. the robotarium (GRITSbots) [138] uses 400 mAh LiPo
battery: This is the onboard energy storage for each robot, allowing them to operate for up to 40 minutes on a single charge, and a Wireless charging system. S-Bot [139] has 12 Volts rechargeable battery for powering of all system. Using external charger battery can be charged as and when required. the r-one robot [142] is equipped with the following energy supply hardware: 3.7V 2000mAh Lithium Polymer (LiPo) Battery, The robot can be charged via the USB port, An additional charging method is available through a docking connector. mROBerTO [143], utilizes the following energy supply hardware: Three 3.7V Li-Po batteries connected in parallel Voltage divider and

ADC port for battery monitoring. In their survey about on swarm robotics material handling and their applications on the conservation of solar energy, Kumar et al [144] they pointed to Li-Po batteries as the primary power source, supplemented by miniature solar panels that harvest solar energy to recharge the batteries and extend their operational time. Additional hardware components like solar charge controllers and power meters are employed to manage and optimize energy usage and storage. The Ri-Bot [145] uses a small 40mAh rechargeable LiPo battery as its main power source. The battery can be conveniently recharged through contacts in the robot's ”eyes” without needing to disassemble the device. With continuous tail movement, the battery provides around 23 minutes of runtime, while intermittent tail usage extends the operating time beyond 1 hour. The HeRo SR, is equipped with 3.7V 1000mAh Li-Po battery and 5V step-up boost converter this converter efficiently steps up the voltage from the 3.7V battery to the required 5V level. Finally the paper of abuelhaija et al [148], The paper describes their SR as being powered by Two rechargeable 4.2V lithium-ion batteries, One battery is dedicated to powering the motor circuit, while the other supplies energy to the control circuit, This separation is likely done to isolate potential electrical noise from the motors and ensure stable power delivery to the sensitive control electronics.

3.4 The Software Design

A “software is the product that software professionals build and then support over the long term. It encompasses programs that execute within a computer of any size and architecture, content that is presented as the computer programs execute, and descriptive information in both hard copy and virtual forms that encompass virtually any electronic media” [154]. The aim of any developped software for SR is to achieve the Swarm behaviour and make this emergent property apear from simple local rules. As for the hardware Nadjah and junior [99] introduce the SR software as a field rich with potential but fragmented, needing greater standardization and direction to transition successfully to real-world applications. Establishing common foundations and embracing techniques like automatic design are highlighted as important steps forward.

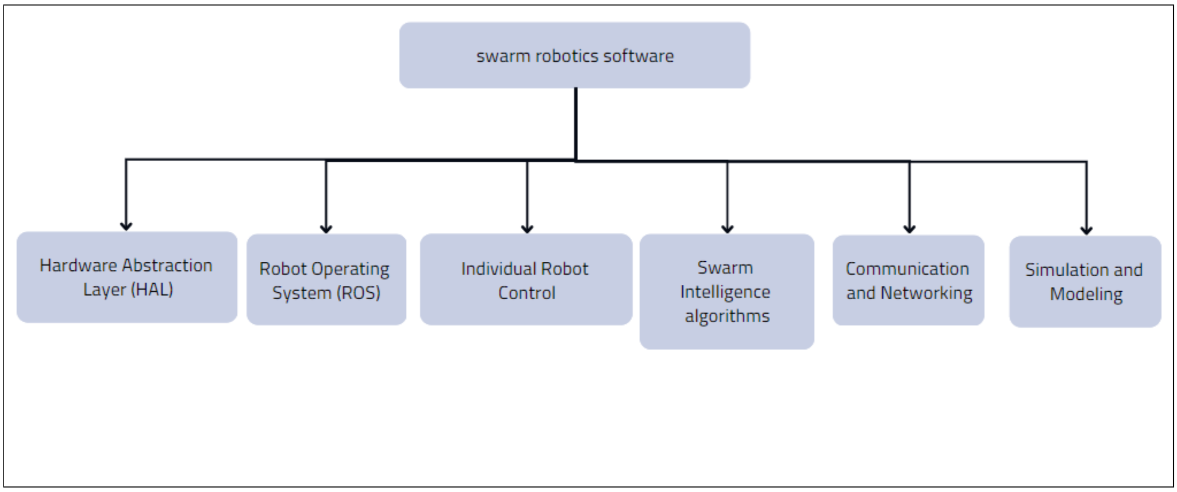


Figure 3.5: Distribution of Scientific Papers in regarding the subject

At the heart of swarm robotics lies the software that enables and governs the collective intelligence and coordination among individual robots. The software components of swarm robotic systems are responsible for tasks, and the implementation of swarm algorithms that dictate the emergent behaviors of the swarm. Starting know the SLR about SR software to synthesize the current knowledge and practices in swarm robotics software development, the 1st paper [121] offers a unique approach to swarm robotics development by providing a software and hardware framework that can be integrated with existing robots This review will specifically focus on the software aspects of SwarmUS, it is compsed of different components citing : HiveMind (core firmware running on Hiveboard), HiveConnect (handles Wi-Fi networking on ESP32), HiveMindBridge (C++ library for host robot communication), Buzz Programming Language (for developing swarm behaviors), HiveAR (Android app for human-swarm interaction), also swarmUS Buzz integration for efficient swarm behavior development Abstraction and modularity for flexible robot integration by the separation between the swarm intelligence (HiveMind) and robot functionalities (HiveMindBridge), it have a Simulation and real-world deployment capabilities its The ability to cross-compile Buzz scripts into ROS nodes and utilize the Gazebo simulator facilitates testing and development before deployment on physical robots, the HiveAR application offers a user-friendly interface for interacting with the swarm. Finally the SwarmUS platform, with its open-source software and hardware, has the potential to accelerate research and development in swarm robotics by Lowering the barrier to entry, Promoting standardization and Enabling real-world applications. Costa et al [132] Design and Development of an Inexpensive Aquatic Swarm Robotics System, The paper details a well-structured and comprehensive software architecture for controlling and managing a swarm of aquatic robots, the software have Onboard Software (Raspberry Controller) Runs on each robot using a Raspberry Pi and Raspbian OS, it uses effectively open-source libraries

(Pi4J, WiringPi) for hardware interaction, promoting code reusability and community involvement. Written in Java, offering platform independence and facilitating development. Handles sensor readings, actuator control, behavior execution, and inter-robot communication. Also it comes with User-friendly interface for monitoring robot locations, headings, and sensor data. It Enables real-time control and deployment of waypoints, geo-fences, and obstacle information, and Logs commands and messages for offline analysis and debugging. For the communication The system utilizes a Wi-Fi network for inter-robot and robot-base station communication. Bartmess et al [133] develop a Fast, Low SR, it comes with a Modular design with separate vision processing and robot control modules promotes clarity and maintainability, it uses an ORB algorithm and vision targets for localization is a well-established approach, and a UDP communication protocol. Finally the paper demonstrates a solid foundation for a low-cost SR system, Addressing the potential concerns and exploring additional features can further enhance the system's robustness, flexibility, and scalability. Regarding Zooids [131] The paper highlights the software architecture enabling complex swarm behaviors and user interaction with the robots. It introduces a layered architecture : an Application Layer (Defines desired swarm behaviors/goals), Simulation Layer, Server Layer (Dispatches commands), Hardware Layer. For the control the zooids uses stratigies like Hungarian Algorithm for efficient swarm reconfiguration, HRVO for real-time collision avoidance, PID control for precise individual robot positioning. It is also Addressing limitations and further development could unlock the full potential of such swarm systems for rich user interactions. The Cellulo paper [129] presents a unique approach to educational robotics with its swarm of small, affordable, and haptic-enabled robots. The software design plays a crucial role in achieving the platform's goals, the software design effectively supports the platform's goals of versatility, practicality and ubiquity in educational robotics. While some limitations exist, the flexible and scalable architecture shows promise for further development and exploration of swarm robotics in education. The architecture is decentralized, it comes with several software components like Vision-Based, haptics controller, Bluetooth 2.1 and a Tablet orchestration software with user interface. the Robotarium [138] software demonstrates a well-designed approach to enabling safe(using the Safety Measures through simulation-based verification and safety barrier certificates) and accessible swarm robotics research, with a focus on simulation-based verification, safety barriers, and user-friendly interfaces. While there are potential areas for improvement, the software's emphasis on safety and accessibility makes it a valuable platform for advancing the field. mROBerTO [143] is another SR platform, regarding the software mROBerTO it comes with Onboard ARM processor allows for complex swarm algorithms, communication via ANT and Bluetooth Low Energy (BLE), Programmed in C++ using open-source SDK for more control. Next is HeRo [146] a SR platform that comes with a ROS integration that Offers modularity and reusability by leveraging existing ROS packages, it Provides standardized communication between robot and external computers, also it uses Simple Arduino firmware focused on essentials like sensors, motors, ROS communication. In Abuelhaija et al paper [148] The robots are programmed in AVR assembly using Atmel Studio, The code is organized into subroutines, promoting modularity and reusability. Each subroutine is likely responsible for a specific task like motor control, sensor reading, or implementing a part of the AI algorithm. The core AI algorithm revolves around interpreting sensor readings and translating them into robot movement. The paper presents a second-order polynomial equation used to determine the relationship between IR sensor readings (representing distance to other robots) and the duration of forward movement. Salman et al [155] provides valuable insights into the automatic design of control software for robot swarms, focusing on economic limitations, they Introduce the "Waffle" platform within the AutoMoDe framework, emphasizing the assembly and fine-tuning of predefined modules for mission-independent control software. Utilizes Probabilistic Finite State Machines (PFSMs) to generate control software, dictating robot actions based on sensor input and internal parameters.Offers flexibility and reduced human intervention, enabling adaptation to different missions and reducing the need for manual programming, it is allowing for mission-specific selection and combination of modules, Optimizes parameters within each module automatically to enhance performance for the chosen mission and all of that can be donne under the economical constraint based on mission requirements, those Economical constraints significantly shape software design and resulting behaviors. Ruenstein et al [156] introduces some algorithms to realise the self assembly behavior in a thousnd SR called kilobots, All Kilobots run an identical program containing the self-assembly algorithm and target shape image, highlighting the decentralized nature of the system with no central controller, They implements three primitive collective behaviors: edge-following, gradient formation, and localization using trilateration between neighbors, These primitive behaviors are combined into a finite-state automaton that dictates each robot's sequence of actions based on its current state and sensor data, its an innovative algorithmic design that enables complex collective self-assembly to emerge from the interaction of many simple robots with limited capabilities, however there is a lack of detailes about the used software. Franceska et al [157] they introduce an automatic method for designing control software for swarm robots which is the AutoMoDe-Chocolate, the paper compares Chocolate with other automatic and manual design methods: beginning with the Reference Model that defines the e-puck robot's capabilities, formalizes sensor inputs and actuator outputs, and provides a consistent comparison platform. Then the Automatic Design Methods like Vanilla that Uses pre-existing modules to create a probabilistic finite state machine with F-Race optimization, EvoStick that evolves a feedforward neural network using evolutionary algorithms and Chocolate that enhances Vanilla with the Iterated F-Race algorithm for better optimization. The Manual Design Methods also has been mentioned like U-Human (Unrestricted design by human experts) and C-Human (Constrained design using the same modules as Vanilla and Chocolate). To optimize and evaluate the design methods a simulator and an objective functions should be used. Hasselmann's phd thesis [158] about "the automatic modular design of control software for robot swarms: using neuroevolution to generate modules" makes a good source of knowledge about the SR software, it focuses on higher-level design methodologies, architectures, and bridging simulation-reality gaps, it introduces the direct neuroevolution and modular neural network behaviors as a Control Software Architecture and it mentions Behavior trees as an alternative. Various AutoMode family members was mentioned as Automatic Design Methods like Chocolate (handcrafted modules), EvoStick (neuroevolution), Arlequin (pre-trained neural modules), Nata (automatic module generation). It is also mentions ARGoS as an offline design simulator. SwarmTalk [159] represents an important step towards standardized cross-platform communication and benchmarking for swarm robotics. Its focus on efficiency, portability and ease of use are valuable for resource-constrained swarms, the paper Addresses critical need for standardized swarm robot communication, it comes with a Portable design with simple driver interface for easy cross-platform use, it has Minimal resource requirements for memory constrained platforms. Buzz [160] is a programming language orionted to SR design, Buzz introduces important innovations like the swarm construct for more nuanced, dynamic swarm behaviors. The extensible design, situated communication, and stigmergy mechanisms provide powerful tools for heterogeneous swarm programming. Francesca and Bittari [161] in their paper highlights the diversity of software approaches used, with a shift towards modularity. However, it emphasizes the need for more structured research, comparisons, and benchmarking in the domain of automatically designing control software for swarm robotics, especially leveraging evolutionary techniques. Establishing standards would enable objective assessment of different software designs and optimization methods, they mentioned the Monolithic Neural Networks, Probabilistic Finite State Machines, Parametric Control Architectures, Modular Architectures. More then that they talk about the Off-line methods using simulations and evolutionary algorithms, and the On-line methods for robots to adapt software while operating, like embodied evolution. Tool kits are so usefull and make the work much easier for the developers, that is what de andrade et al [162] offers by Pyswarming which is a valuable contribution enabling swarm robotics research by prioritizing behavior implementation in a cross-platform, Python-based package. Its strengths include accessibility, existing algorithm library, simple simulation, and customizability. This paper [163] presents a layered software architecture for autonomous UAV swarms designed for firefighting with an architecture built on ROS, This software architecture boasts a modular design, with a layered approach (four layers) that enables independent development and testing, enhancing scalability and future improvements. It features efficient path planning using a PRM-based global path planner to generate optimal paths for each UAV, considering formation types. Line-of-sight smoothing further optimizes paths, reducing mission time. Robust collision avoidance is achieved through both centralized and decentralized methods, ensuring safe navigation by managing inter-UAV collisions and detecting static/dynamic obstacles. Deep Reinforcement Learning (DRL) empowers UAVs with autonomy, enabling them to make informed decisions for obstacle avoidance and trajectory optimization in unknown environments. Toolkits are very usefull to developpers in all CS branches for facilitating, in the case of SR Akkaya et al [164] they present PILOT, a software toolkit designed for creating data-intensive distributed applications in robotic swarm scenarios, PILOT presents an innovative actor-oriented paradigm well-suited for modular swarm programming. Its explicit state-space modeling, streaming data handling, and machine learning integration are strengths. Nevertheless, there is a lack of presented informations about algorithm library, implementation specifics, scalability evaluation, and scope of learning integration to fully assess its effectiveness as a comprehensive swarm software toolkit. Swarmie project [165], is a swarm robotics platform developed at NASA Kennedy Space Center, it comes with Strong choice of ROS framework providing modularity, inter-process communication, standard message types, UI tools, and simulation capabilities; it promotes code reuse and collaboration. This approach aligns with the sound design principle of separating functionality into distinct modular nodes, enhancing the system's scalability and maintainability. In terms of designing SR software Brambilla et al [166] presents a novel approach to designing swarm robotics software called "Property-Driven Design". Instead of the traditional "code-and-fix" method, it advocates a top-down approach focusing on desired properties and formal verification through model checking, The property-driven design approach presents a promising formal methods-based alternative to traditional "code-and-fix" methods, in terms of Formal Specification & Verification The use of PCTL and Markov chains allows for formally specifying desired swarm behaviors and verifying them through model checking. This helps ensure the software achieves intended goals, reducing the risk of unexpected outcomes. Property-driven design prioritizes design over implementation details. By promoting the idea of prescriptive model that acts as a blueprint. The four-phase approach provides a structured framework for development, enhancing clarity and reducing reliance on ad-hoc methods. Gansari and Buiu [167] presents a novel approach to integrating heterogeneous swarms of robots through a ROS-based software framework. The proposed system effectively addresses the challenge of integrating robots with different hardware and software characteristics. This is crucial for real-world applications where diverse robot capabilities are needed. The system integrate ROS as the backbone provides several benefits like Modularity(by using ROS nodes), Scalability (ROS's network capabilities making the system scalable to larger swarms), Flexibility(The five working modes) and finally it is open source. Chamanbaz et al [168] describes a hardware/software suite to enable swarming behavior in a

variety of robots. The software, a Python module called "marabunta," exhibits several noteworthy features:
-Modular design: separating robot control "body", communication "network", and swarming behavior "behavior" into distinct classes.
-Platform agnostic : different robots can be integrated by creating platform-specific body classes (eBot and e-puck examples given).
-Communication flexibility and Enables heterogenity.
-Provides "MockBody" and "MockNetwork" classes for simulation and rapid prototyping of swarm algorithms without real hardware. And it is Python-based for ease of development.

Parker et al [169] provides a broad overview of multi-robot systems with a particular emphasis on hardware. While it mentions some specific software examples. While the paper focuses primarily on hardware aspects, it touches on important swarm software principles like behavior-based control that uses simple reactive behaviors that combine into emergent swarm behavior, Distributed algorithms for swarm behaviors like dispersion, leader following, clustering, it uses Simulation tools for developing and testing swarm algorithms before physical deployment. Back to franceska et al [170] they develope Vanilla first in 2014 then chocolate in 2015, chocolate has been mentioned earlier in this review, know talking about vanilla, paper focuses on comparing different approaches to designing control software for swarm robots, specifically for the e-puck robot platform. The software architectures compared are:
1.AutoMoDe-Vanilla (Vanilla): This is an automatic design method that uses a modular approach. It assembles pre-existing parametric modules representing low-level behaviors (like exploration, phototaxis, attraction, etc.) and conditions (like black-floor, neighbor-count, etc.) to synthesize control software in the form of a probabilistic finite state machine.
2. EvoStick: This is an implementation of evolutionary robotics for automatic design. It uses a feed-forward neural network without hidden nodes, where the network's parameters are optimized using a standard evolutionary algorithm.
3. U-Human: This is a manual design approach where human experts have complete freedom to design the control software using an API that accesses the robot's sensors and actuators.
4. C-Human: This is another manual design approach where human experts are constrained to use the same control architecture and parametric modules available to Vanilla.
The project emphasizes a modular design approach, particularly in the Vanilla and C-Human methods, which uses pre-existing modules to restrict the design space. This strategy helps to mitigate the reality gap—the difference between simulation and real-world performance. Both Vanilla and C-Human utilize a probabilistic finite state

machine (PFSM) architecture, balancing complexity and interpretability, making it suitable for representing the behaviors of robot swarms. In contrast, EvoStick employs neural networks, offering greater representational power but at the risk of overfitting, which can increase the reality gap. This paper [171] explores the using of behavior trees as a control architecture for automatically designing swarm robot software. It presents a new method called Maple, which assembles and fine-tunes pre-existing modules into a behavior tree. It introduces a Novel application of behavior trees to automatic swarm control design, Allows complex behaviors by combining subtrees Greater expressiveness with two-way control transfers and Validated with real-world e-puck robot experiments Showed comparable or superior performance to other methods. Gianduja [172], is an automatic design method for generating communication-based behaviors in robot swarms. The paper focuses on the software design process and evaluates the resulting control software through simulations and physical experiments, it is a framework that automatically designs control software for robot swarms using Probabilistic Finite State Machines (PFSMs). It utilizes a modular design approach, allowing for flexible and reactive behavior based on probabilistic rules. Robots communicate via a single, locally broadcasted message with emergent semantics, meaning its interpretation depends on the evolved behavior. It belongs to the AutoMode familly, it uses the IRACE optimization algorithm to efficiently search for the optimal PFSM configuration that maximizes mission-specific performance, it is really the IRACE optimization algorithm to efficiently search for the optimal PFSM configuration that maximizes mission-specific performance

3.5 Answering the research questions

Based on the information provided by conducting the review on the papers the answers of four questions will be as follows:

3.5.1 What is the hardware architecture needed for SR?

Starting from the conducted review as a foundation, it can be seen that there are two parts process to design a SR in the general approach:
-Hardware Design: Focuses on choosing the right actuators, sensors, communication modules, and power sources based on the specific environment and task.
-Software Design: Emphasis is placed on developing software that enables emergent swarm behavior, often inspired by natural swarm intelligence algorithms. The software needs to manage the robot actions, communication, and coordination.
About the components:
The hardware: composed of various parts:
Actuators: DC motors, servo motors, wheels, legs, propellers, vibration motors, and specialized mechanisms for buoyancy (in aquatic robots).

Sensors: Infrared (IR) sensors, ultrasonic sensors, cameras, GPS, chemical sensors, temperature sensors, humidity sensors, and touch sensors.
Communication: Bluetooth, Wi-Fi, ZigBee, RFID, IR, and even electric field detection in aquatic robots.
Power Sources: Rechargeable batteries (often LiPo), solar panels, and charging systems.
This hardware can variate regarding:
-Environment: Different environments require specialized actuators and sensors (e.g., propellers for water, wings for air).
-Task: The specific task influences the hardware selection (e.g., cameras for navigation, chemical sensors for environmental monitoring).
-Economic Constraints: Budgetary limitations may dictate the choice of more affordable components.

3.5.2 What are the software that the SR should come with?

The Software is very essentiel for the swarming behavior to emerge from local rules and local intractions between individual robots, so the software based on the conducted review is:
-Individual Robot Control: Handling sensor data, controlling actuators, and executing basic behaviors.
-Inter-Robot Communication: Facilitating information exchange and coordination.
-Swarm Behavior Implementation: Implementing algorithms that create emergent swarm behaviors (e.g., collective navigation, task allocation, self-assembly).
-Human-Swarm Interaction: Providing interfaces for human users to control and monitor the swarm.
-Programming Languages: Choice of language depends on the platform, complexity, and developer preferences.
-Frameworks: These provide common infrastructure and libraries for easier development, simulation, and deployment.
There are real platforms that used to achieve the swarm behavior and to design and build swarm robots like Like AutoMoDe-Chocolate, Vanilla, and Maple. This mentioned software can be merged with machine learning technics for better swarm coordination.

3.5.3 What are the future explorations of SR with identifying the gaps in the rviewed papers?

Firstly, the standardization across SR hardware and software platforms is urgently needed. Establishing common protocols and architectures will facilitate wide-scale adoption, collaboration, and interoperability between different SR systems.

Automatic design of software for SR is another critical research frontier, Continued development of modular architectures is essential for achieving greater flexibility and scalability in SR systems. Modular designs will allow for rapid reconfiguration, adaptation to dynamic environments, and the ability to seamlessly integrate new robotic agents or functionalities into existing swarms. Also The integration of swarm robotics with advanced machine learning and artificial intelligence techniques holds immense promise. By imbuing individual robots with learning capabilities and enabling the swarm to collectively process and adapt to data, we can create highly sophisticated, intelligent, and adaptive swarm systems.

Finally, the exploration of new materials, miniaturization techniques, and energy harvesting technologies will further expand the capabilities of swarm robotics. Developing smaller, more efficient, and self-sustaining robotic agents will enable swarms to operate in increasingly challenging environments and for extended durations.

About the gaps in the reviewed papers regarding the hardware gaps is the Standardization: The most significant gap is the lack of a universal design methodology or standardized hardware platform. This makes it difficult to compare results, share code, or easily migrate projects between platforms.

The Economic Constraints: The need for low-cost SR is emphasized, but few papers provide detailed comparisons of different cost-effective hardware options. More research on balancing performance with cost is needed. However the paper that has been reviewed earlier in this review and it was written by salman et al presents waffle platform, a significant advancement in automatic design methods for SR by tackling the concurrent design of control software and hardware under economic constraints. Environmental Adaptation: The papers mainly focus on specific environments (ground, water, air). More research is needed on creating adaptable SR that can operate in diverse and changing environments.

Self-Repair and Robustness: There's limited discussion on building SR that are robust and can self-repair in challenging environments.

Regarding the gaps in the software papers: Automatic Design Methods: While automatic design methods show promise, they are still under development. More research is needed on their effectiveness.

Communication Protocols: There's a need for standardized, efficient, and robust communication protocols for SR. Existing protocols often lack scalability and flexibility.

Swarm Behavior Modeling: Developing robust models and tools for predicting and analyzing swarm behavior is important for designing effective SR.

Real-World Deployment: Many papers focus on simulation or small-scale experiments.

Human-Swarm Interaction: While some papers mention interfaces, more research is needed on designing intuitive and user-friendly interfaces that enable effective human control and management of large-scale swarms.

Ethical Considerations: The ethical implications of using SR are rarely discussed.

3.6 Conclusion

This was a SLR conducted on written SR papers in the last 10 years about the hard/-software of the SR, following a rigorous process and presented a wealth of information on both hardware and software aspects, offering a wide variety of information about it. And thus The study underscores the importance of both hardware and software in enabling swarm behaviors, inspired by natural swarm intelligence algorithms, The hardware components include actuators, sensors, communication modules, and power sources and it is varied depending on the environment, tasks and cost. On the software side, the emphasis is on developing emergent behaviors, inter-robot communication, and human-swarm interaction. The review identifies critical gaps in the existing research, such as the need for standardization across SR platforms. integrating modular architectures for flexibility and scalability, The incorporation of advanced machine learning and artificial intelligence techniques promises to enhance the adaptability and intelligence of swarm systems, it introduces also the future exploration in the field. So while there has been substantial progress, the field of swarm robotics requires further research and development to fully realize its potential in various applications.

Chapter 4

Creation of the swarm robot(Experimental)

swarm robots, are robots with specific features that enables the swarm behavior to emerge from simple local rules, features like: scalability, adaptability, robustness and been autonomous which is a feature that have its root back to the decentralized nature of swarming, creating a swarm of robots is hard due to several constrains like the financial one the time consuming one the lack of standardization in the hard/software of SR, the absence of equipped laboratory, all that constraint disable the ability of the creation of a full SR system with all its features, creating just two robots which is the case this project isn't compatible with the mentioned feature of robustness because if one robot faill the whole system does, it is mentioned earlier that the number of the robots should be between 10^2 and the avogadro number, less then 10^2 its hard to the swarm behavior to clearly emerge. Also like it is already mentioned earlier in the thesis bartmass et al has built 16 fast, low SR with a budget of 31000$, one more thing is that is hard to create a decetralized system with such constraints. So it turns out to create in this project two swarm robots with centralized system and an algorithm that is close in its concept to the concept of one of SI algorithms which is master-slave algorithm that is nearly similair to follow the leader algorithm it is the centralized version of it, so the goal is to approximately mimic the swarm behavior. However, Dimakos et al [173] Do ''A Study on Centralised and Decentralised Swarm Robotics Architecture for Part Delivery System'' and they discusses the concepts of centralized and decentralized SR:

Centralized Swarm Robots: it involves a single controller or a small number of controllers making decisions for the entire swarm.These systems can potentially optimize overall swarm behavior efficiently because of the global perspective of the central controller. However, they suffer from several drawbacks beside the ones cited above, such as a single point of failure, scalability issues, and higher communication overhead.

Decentralized Swarm Robots: Decentralized systems distribute the decision-making process across all robots in the swarm. Each robot operates based on local information and simple local rules, leading to robust and scalable behavior. Decentralized control mimics natural swarm intelligence, like that seen in ant colonies or flocks of birds, and is more fault-tolerant. These systems are more adaptable to dynamic environments because each robot can independently respond to changes.

To conclude with, Decentralized systems are generally preferred for swarm robotics due to their robustness, scalability, and adaptability. On the other hand, Centralized systems while it is potentially more efficient in certain aspects, it faces significant practical limitations that make them less suitable for large-scale or dynamic applications. Another work conducted by Hu et al [174] from Cornell University explores the trade-offs between centralized and decentralized control in swarm robotics.

	Centralized	**Decentralized**
Advantages	• typically yields higher quality decisions because of its global view • can better utilize available resources due to their comprehensive view of the state of all devices.	• control scales better as each edge device independently pulls tasks • lower latency because each device makes its own decisions.
Disadvantages	• scalability issues as the swarm size increases. • it can become bottleneck with large, heterogeneous swarms.	• each device only has local visibility of its own state and resources. • limited resources compared to centralized.

The paper utilizes both a physical prototype of 12 programmable drones and a scalable event-driven simulator to evaluate the performance and scalability of centralized and decentralized control systems, it suggests that hybrid models, combining elements of both centralized and decentralized control, could mitigate some of the disadvantages of each approach.

Navarro et al[175] This paper compares centralized and decentralized approaches for learning flocking behaviors in a swarm of robots using particle swarm optimization (PSO). Centralized learning:Uses a single controller copied to all robots, Evaluates the swarm behavior using a global fitness metric, and Achieves higher fitness and lower standard deviation than decentralized approaches, But it takes 4x longer evaluation time per iteration than decentralized. Decentralized learning: Distributes different controllers to each robot Uses a local fitness metric evaluated independently on each robot, and Allows faster evaluations by parallelizing across robots, also two variants tested with individual movement factor and group movement factor in local metric Group movement factor matches global metric better but suffers from credit assignment problem Lower fitness and higher variance than centralized, but best solutions still learned the desired flocking.

LI et al [176] focuse on a centralized approach to controlling and coordinating SR (ROBOTRAK), The ROBOTRAK server collects data from each robot in the swarm, including location, neighboring robots, and other relevant information. This provides a centralized view of the swarm's state(centralized monitoring), also The server issues commands to individual robots or the entire swarm, such as moving to a specific location, joining or leaving the swarm. This control is not autonomous (centralized control), ROBOTRAK assists in situations like swarm partitioning or isolated robots. It provides the algorithm and guidance to reconnect the swarm (centralized coordination).

4.1 The Hardware Design

The hardware of a robot is the physical embodiment of its capabilities, It is the hardware that executes the instructions dictated by the software, translating them into physical actions. In this section the hardware used in this project will be introduced and explained, as it is clarified earlier in the SLR section the general hardware components that can be found in nearly any robot are: Actuators and locomotion mechanisms, sensors, Communication and networking, Power supply.

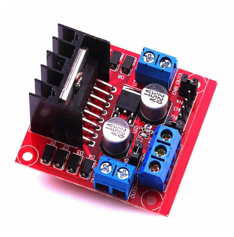
4.1.1 Actuators and locomotion mechanisms

as it is mentioned earlier ‘’actuators move or actuate the joints and links of the robot as per the signals given by the controller. the actuators help the robot to withstand the forces of gravity, inertia’’. The used actuators and motion mechanisms in this project are:

four BO1 motors and four BO1 wheels and four castor wheels: BO1 motors are widely available and affordable, These motors generally operate between 3V to 12V DC, they are are available in 100 RPM, 200 RPM, and 300 RPM variants (RPM rating indicates the speed of the motor under no-load conditions), BO1 motors are small and lightweight, making them ideal for small size robots, Their low current draw (40-80mA) allows for longer battery life.

(a) B01 motors + B01 wheels[?]

(b) Castor wheel[177]

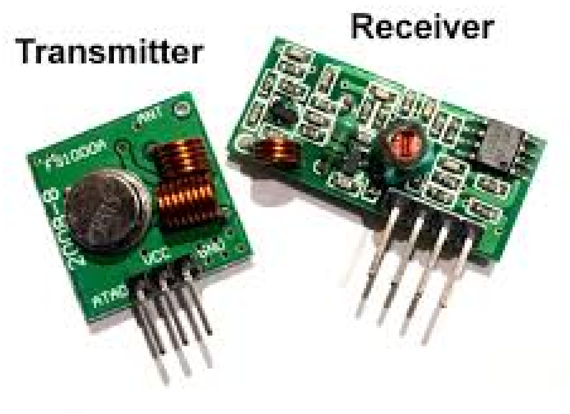


(a) L298N motor driver[178]

(b) Castor wheel[179]

(a) wooden chassis

(b) 9V battery



(a) RF transmitter and receiver

L298N motor driver: The L298N motor driver is a popular choice for controlling DC motors it contains two full H-bridge drivers to control two DC motors, It can handle motor supply voltages up to 46V, The logic part of the L298N can be powered by a separate supply ranging from 5V, Use PWM signals on the ENA and ENB pins to control the speed of the motors.

4.1.2 sensors

in this project two IR sensors are used both in the master robot to follow the black line that don't reflect the light. Infrared (IR) sensors are widely used in various applications for detecting objects, measuring distances, and sensing environmental conditions. There are two types of IR Sensors:Proximity Sensors(the one we gonna use in the project) Emit infrared light and detect reflections to determine the presence or distance of objects. And Passive IR Sensors Detect infrared radiation emitted by warm objects, such as humans and animals, used primarily in security systems and automatic lighting. Proximity sensors works by An IR LED within the sensor emits invisible infrared light,This light beam hits the object and reflects back towards the sensor. A receiver within the sensor detects the reflected light. The intensity of the reflected light determines the distance of the object.

4.1.3 Communication and networking

Radio Frequency (RF) technology allows for wireless communication by transmitting and receiving electromagnetic waves, The transmitter converts information (like audio, data, or control signals) into an electrical signal, This electrical signal is then modulated onto a carrier wave, which is a high-frequency radio wave, The modulated signal is amplified to increase its power and reach further distances, The amplified signal is then transmitted through an antenna. While the RF receiver antenna captures the electromagnetic waves transmitted by the transmitter, The receiver then demodulates the received signal, separating the information from the carrier wave, The demodulated signal is amplified to improve its strength and clarity, finally The amplified signal is then decoded to recover the original information.

4.1.4 power supply

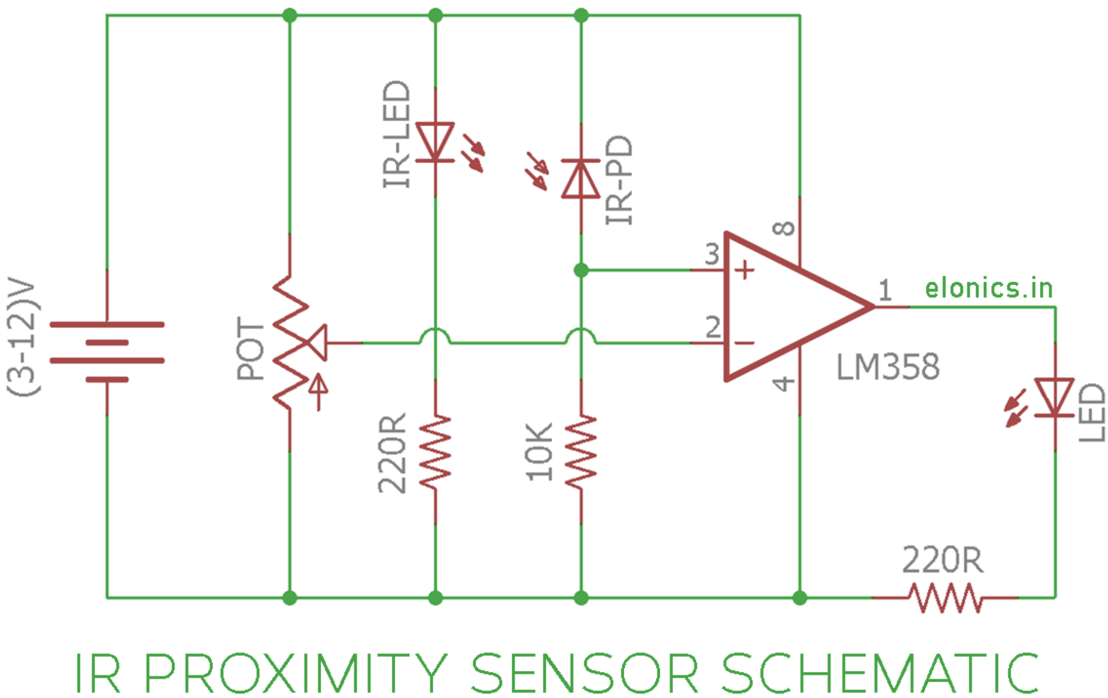
in this project four 9V Alkaline batteries used as power supply, two per robot, it have Two snap connectors on the top, with one positive and one negative terminal, They have a long shelf life, typically around 5 to 10 years, making them reliable for emergency use. Alkaline batteries are a versatile and reliable power source for a wide range of applications .

4.1.5 microcontroller

The ATmega microcontroller have series, an ATmega328P will be used in this work, it is an 8-bit microcontroller from Microchip Technology, commonly used in the Arduino platform specialy the arduino uno, with a RISC architecture and operation frequency that is Up to 20 MHz, 32 KB for program storage, 2 KB for runtime data, and 1 KB for non-volatile data storage. For the peripherals there are 23 general-purpose I/O pins, 6 channels with 10-bit ADC for the analog inputs and 6 PMW channels.

4.1.6 Bread-boards

in this work two breadboards will be used, a breadboard is a rectangular plastic board with a grid of holes that allows you to quickly and easily build and test electronic circuits. The holes are connected with metal strips inside the board, creating rows and columns that provide electrical connections.



(a) IR Sensor circuit diagram

4.1.7 wooden chassis

in this project a superposed chassis use for both robots the 1st floor assembled with two wheels on the sides and two castor wheels on the bottom of it, on the top we find the two 9 volte batries. the 2nd floor equipped with the arduino uno, the bread board, the motor driver, in the master robot the rf transmitter and the receiver is on the slave robot.

4.2 The software design

The software acts as the intelligent core, providing a virtual environment that governs the robot's operations, in this case the Arduino itself is the governer of robots operations, arduino is a hardware and software platform designed for building and programming microcontroller-based projects, The arduino IDE supports a simplified version of C++ and includes a rich library ecosystem for various functionalities like controlling sensors, displays, and communication modules. However The Arduino Core is the set of libraries and tools that allows the Arduino IDE to support a particular microcontroller or board. It provides the necessary abstraction to interact with hardware components.

4.2.1 IR sensors & Arduino

first Connect the VCC pin of the IR sensor to the 5V pin on the Arduino, then Connect the GND pin of the IR sensor to the GND pin on the Arduino, Connect the GND pin of the IR sensor to the GND pin on the Arduino, after Connect the analog output pin of the IR sensor to an analog input pin on the Arduino(in our case the righr IR to the A0 and the left to A1) the IR sensor then can be used in various applications like distance measurement (in our case Using IR sensors to detect and follow lines on the ground), also there are libraries in the arduino platform that deal with sensors like Irremote, New ping and adafruit sensor library.

4.2.2 Arduino & Motor Drives

The motor driver acts as an interface between the Arduino and the motors, allowing the controll of speed and the direction. For the hardware setup connect first Connect IN1 and IN2 to digital pins on the Arduino (pin 2 and 3 in our case) for motor A, and IN3 and IN4 to other digital pins (pin 4 and 5) in our case. Then Connect the motors to the output terminals (OUT1, OUT2 for motor A, OUT3, OUT4 for motor B) on the L298N, after Connect an external power supply (9V battery) to the motor driver's VCC and GND terminals. Connect the Arduino's 5V to the motor driver's 5V pin if needed. We can use ENA and ENB to controll the speed of the motors.

4.2.3 Arduino & RFT/R

Using RF ''Radio Frequency'' transmitter and receiver 433mhz modules with an Arduino Uno allows you to wirelessly transmit and receive data between two Arduino boards. RFT connections : the VCC Connected to the 5V pin on the Arduino(in our case the connection happend with the intervenes of the breadboard). The GND of

the RFT Connect to the GND pin of the Arduino(in our case the connection happend with the intervenes of the breadboard). And the last one the DATA one connected to a digital pin on the Arduino (which is 12th pin in our case).
RFR connections: the VCC Connected to the 5V pin on the Arduino(in our case the connection happend with the intervenes of the breadboard). The GND of the RFT Connect to the GND pin of the Arduino(in our case the connection happend with the intervenes of the breadboard). And the last one the two DATA ones connected to a digital pin on the Arduino (which is 11th pin in our case) with the intervenes of the breadboard. Arduino IDE comes with a library called ''RadioHead'' that used to deal with RFT/R communication.

4.2.4 Programming Language

The Arduino programming language is a simplified version of C++ designed to make it easy to write code for the Arduino microcontroller boards. It combines elements of C and C++, It uses a simplified setup that includes two main functions: setup() and loop(), the first one runs once when the Arduino is powered on or reset. It's used to initialize variables, pin modes, start using libraries. The second one runs continuously after setup(). It contains the main code that needs to be executed repeatedly. Arduino provides a large number of libraries that add additional functionality, The Arduino language includes many built-in functions to control hardware, such as digitalWrite(), digitalRead(), analogRead(), analogWrite(), delay()..etc the arduino code called sketch.

4.2.5 Algorithm

the algorithm used in this project is master slave algorithm, an algorithm that we cosidered her as the centralized version, of follow the leader algorithm.
1-master algorithm:
Start
1. Setup

- Initialize Serial Communication
- Initialize RF Driver
- If Initialization Fails: Print "init failed"

- Configure Motor Control Pins (B1, B2, B3, B4) as OUTPUT

- ◦ Configure Sensor Pins (A0, A1) as INPUT

2. Loop

- Read Right Sensor (A0)
- Read Left Sensor (A1)
- Print Sensor Values
- Decision
- If Right == HIGH and Left == HIGH: Move ”Forward”
- If Right == LOW and Left == LOW: Move ”Stop”
- If Right == HIGH and Left == LOW: Move ”Right”
- If Right == LOW and Left == HIGH: Move ”Left”

3. Move Command

- Send Decision via RF
- Print decision
- Execute decision
- if”Forward”: Set B1 LOW, B2 HIGH, B3 LOW, B4 HIGH
- if”Backward”: Set B1 LOW, B2 HIGH, B3 LOW, B4 HIGH
- if”Right”: Set B1 HIGH, B2 LOW, B3 LOW, B4 HIGH
- if”Left”: Set B1 LOW, B2 HIGH, B3 HIGH, B4 LOW
- if”Stop”: Set B1 LOW, B2 LOW, B3 LOW, B4 LOW

4. Repeat Loop

2-slave algorithm:
Start

- Initialize Serial Communication at 9600 baud and RF Driver
- If RF Driver initialization fails

- Print ”init failed”
- Configure motor control pins B1, B2, B3, B4 as OUTPUT
-

Loop:

- Attempt to receive command via RF
- If command received:
- Null-terminate received string
- Convert received data to string (command)
- Print ”Received: [command]”
- Execute move(command)
- Function move(command):
- If command == ”Forward”:
- Set B1 HIGH
- Set B2 LOW
- Set B3 HIGH
- Set B4 LOW
- Print ”Forward”
- If command == ”Backward”:
- Set B1 LOW
- Set B2 HIGH
- Set B3 LOW
- Set B4 HIGH
- Print ”Backward”
- If command == ”Right”:
- Set B1 LOW
- Set B2 HIGH
- Set B3 HIGH

- Set B4 LOW
- Print "Right"
- If command == "Left":
- Set B1 HIGH
- Set B2 LOW
- Set B3 LOW
- Set B4 HIGH
- Print "Left"
- If command == "Stop":
- Set B1 LOW
- Set B2 LOW
- Set B3 LOW
- Set B4 LOW
- Print "Stop"

4.2.6 master robot code

```
#include <RH_ASK.h>
#include <SPI.h>

RH_ASK driver;


#define B1 2
#define B2 3
#define B3 4
#define B4 5

void setup() {
  Serial.begin(9600);
  if (!driver.init()) {
    Serial.println("init failed");
  }

  pinMode(B1, OUTPUT);
  pinMode(B2, OUTPUT);
  pinMode(B3, OUTPUT);
  pinMode(B4, OUTPUT);
  pinMode(A0, INPUT);
```

```
  pinMode(A1, INPUT);
}

void sendCommand(const char* command) {
  driver.send((uint8_t *)command, strlen(command));
  driver.waitPacketSent();
  Serial.print("Sent: ");
  Serial.println(command);
}

void move(String motion) {
  if (motion == "Forward") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, HIGH);
    digitalWrite(B3, LOW);
    digitalWrite(B4, HIGH);
  } else if (motion == "Backward") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, HIGH);
    digitalWrite(B3, LOW);
    digitalWrite(B4, HIGH);
  } else if (motion == "Right") {
    digitalWrite(B1, HIGH);
    digitalWrite(B2, LOW);
    digitalWrite(B3, LOW);
    digitalWrite(B4, HIGH);
  } else if (motion == "Left") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, HIGH);
    digitalWrite(B3, HIGH);
    digitalWrite(B4, LOW);
  } else if (motion == "Stop") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, LOW);
    digitalWrite(B3, LOW);
    digitalWrite(B4, LOW);
  }

  sendCommand(motion.c_str());
  Serial.println(motion);
}

void loop() {
  int Right = digitalRead(A0);
  int Left = digitalRead(A1);

  Serial.print("Value of Right sensor is: ");
  Serial.print(Right);
```

```
  Serial.print("\tValue of Left sensor is: ");
  Serial.println(Left);
  delay(100);

  if ((Right == 1) && (Left == 1)) {
    move("Forward");
  } else if ((Right == 0) && (Left == 0)) {
    move("Stop");
  } else if ((Right == 1) && (Left == 0)) {
    move("Right");
  } else if ((Right == 0) && (Left == 1)) {
    move("Left");
  }
}
```

4.2.7 slave robot code

```
#include <RH_ASK.h>
#include <SPI.h>
RH_ASK driver;
#define B1 2
#define B2 3
#define B3 4
#define B4 5

void setup() {
  Serial.begin(9600);
  if (!driver.init()) {
    Serial.println("init failed");
  }
  pinMode(B1, OUTPUT);
  pinMode(B2, OUTPUT);
  pinMode(B3, OUTPUT);
  pinMode(B4, OUTPUT);
}
void move(String motion) {
  if (motion == "Forward") {
    digitalWrite(B1, HIGH);
    digitalWrite(B2, LOW);
    digitalWrite(B3, HIGH);
    digitalWrite(B4, LOW);
  } else if (motion == "Backward") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, HIGH);
    digitalWrite(B3, LOW);
    digitalWrite(B4, HIGH);
  } else if (motion == "Right") {
    digitalWrite(B1, LOW);
```

```
    digitalWrite(B2, HIGH);
    digitalWrite(B3, HIGH);
    digitalWrite(B4, LOW);
  } else if (motion == "Left") {
    digitalWrite(B1, HIGH);
    digitalWrite(B2, LOW);
    digitalWrite(B3, LOW);
    digitalWrite(B4, HIGH);
  } else if (motion == "Stop") {
    digitalWrite(B1, LOW);
    digitalWrite(B2, LOW);
    digitalWrite(B3, LOW);
    digitalWrite(B4, LOW);
  }

  Serial.println(motion);
}

void loop() {
  uint8_t buf[RH_ASK_MAX_MESSAGE_LEN];
  uint8_t buflen = sizeof(buf);

  if (driver.recv(buf, &buflen)) {
    buf[buflen] = 0;
    String command = String((char*)buf);
    Serial.print("Received: ");
    Serial.println(command);
    move(command);
  }
}
```

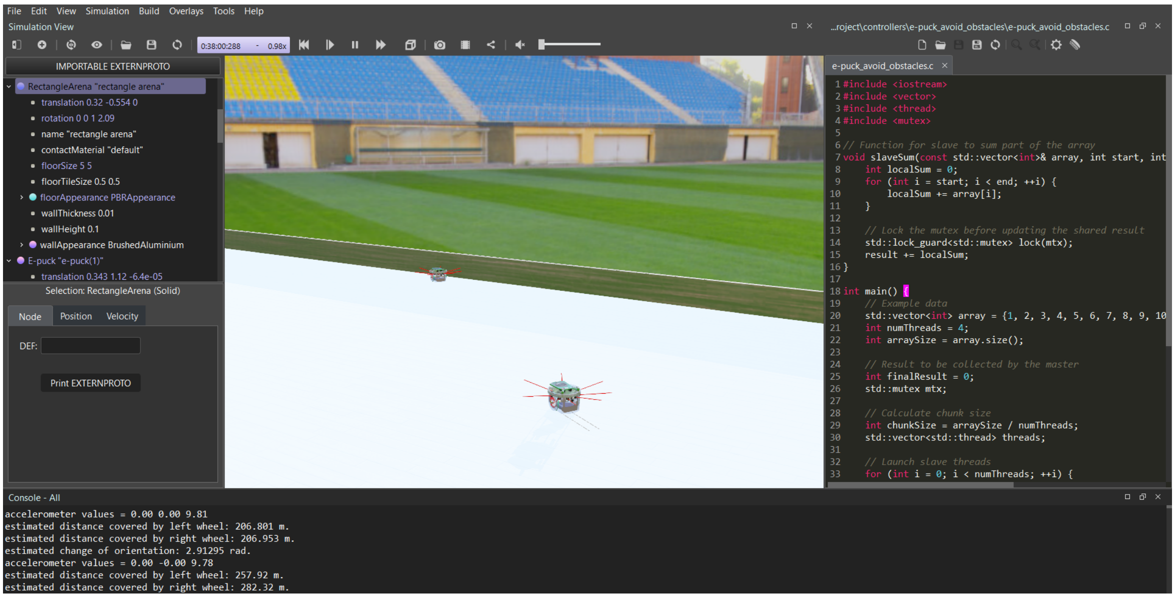
4.2.8 4SA

designed to provide a simple interface for programming Arduino boards. It is particularly useful for educational purposes, allowing users (especially beginners and kids) to create interactive projects without needing to write complex code, so this app used in this work in the beginning as a tool to build a prototype of the work before writing the code and building the robot, it is a Drag and drop interface based on Scratch, it is used to Create interactive projects.

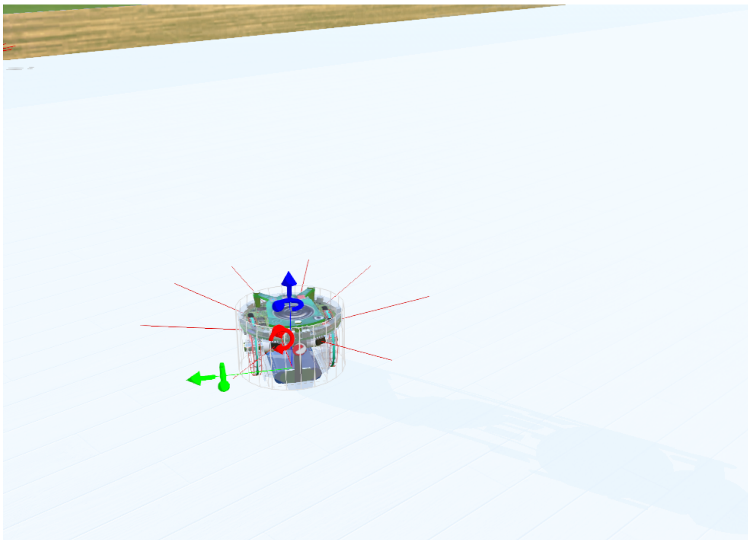
4.2.9 Simulation

Simulating swarm robotics is essential for understanding, designing, and testing swarm behaviors without the cost and complexity of working with physical robots as it mentioned earlier in this thesis that the vast majority of the conducted research in this field done using simulation, in this work webots simulator is used for simulating master slave algorithm and then follow the leader algorithm, the simulation conducted using E-Puck swarm robots in both the master-slave and FTL algorithms.

Simulation of master slave algorithm

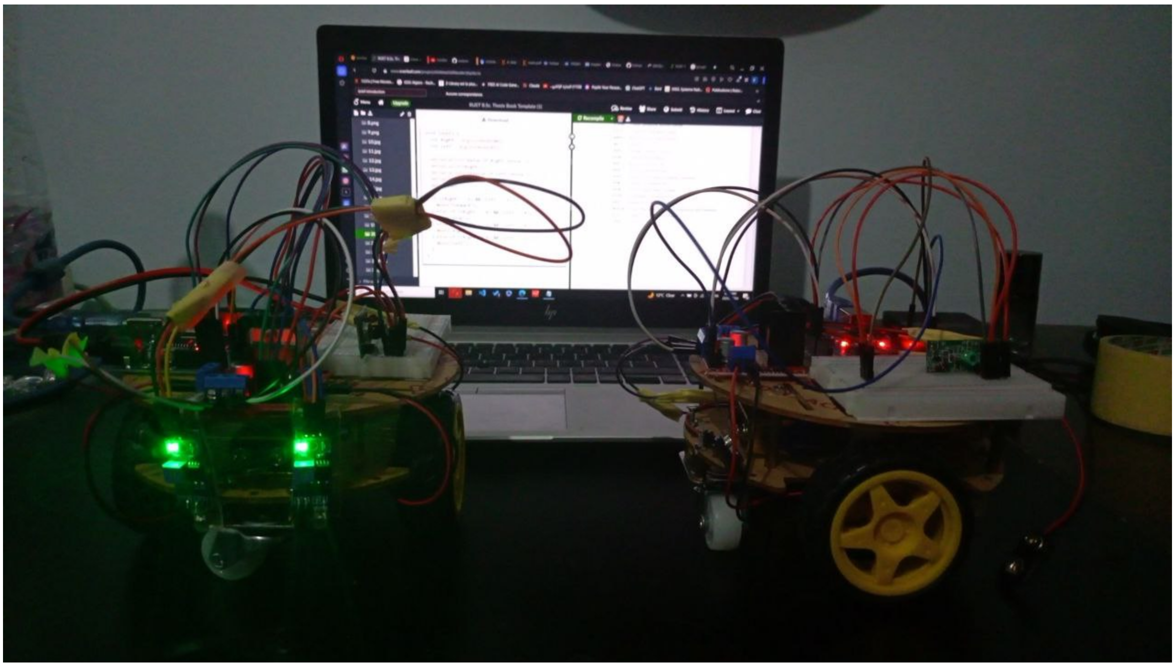


(a) simulation of master-slave algorithm using epuck robot from webot platform



(a) the E-puck Root

4.3 final result the T-bot



(a) Two T-bots

Chapter 5

Follow The Leader Algorithm

FTL is a Metaheuristic optimization algorithm, Metaheuristic optimization approaches have proven itself superior to the traditional optimization approaches [180], metaheuristic algorithms are divided into four classes [181]: Evolution-based algorithms, Swarm-based algorithms, Physics-based algorithms, Human-based algorithms. FLT is a simple yet commonly used technique in swarm robotics and multi-agent systems. It involves one or more robots (or agents) designated as leaders, with the remaining robots (followers) programmed to follow these leaders, it is inspired from the movement of sheep within a flock. The basic idea is to simulate the behavior of sheep following a leader to find optimal solutions to a given problem.

5.1 The general structure of the algorithm

1-Initialization:
-Initialize a population of N sheep (solutions) randomly within the search space.
- number of iterations, step-size parameters.
2-Fitness Evolution:
-Evaluate the fitness of each sheep in the population using the objective function f(x).
3-Leader Selection:
-Identify the leader (the sheep with the best fitness value).
4- Movement Update:
For each sheep in the population (excluding the leader), update its position based on the following rule:

$$X_i(t+1) = x_i(t) + \alpha \cdot \mathrm{rand}(x_{\mathrm{leader}}(t) - x_i(t))$$

where:

$$x_i(t)$$

is the position of the i-th sheep at iteration t.

$$x_leader(t)$$

is the position of the i-th sheep at iteration t.

$$\alpha$$

is the step-size parameter.
rand is a random number between 0 and 1.
5-Step-Size Adjustment:
This can be done using a decreasing or increasing strategy such as:

$$\alpha(t) = \alpha_0 \left(1 - \frac{t}{\text{max-iteration}}\right)$$

where:

$$\alpha_0$$

is the initial step-size. 6-Boundary Check
7-Convergence Check:
Check the convergence of max iterations and the fitness function.
8-Update Iteration:
Increment the iteration counter and return to step 2.

5.2 The used code for simulation in webot simulator: (the code written in python)

```
from controller import Robot, Motor, DistanceSensor
robot = Robot()
timestep = int(robot.getBasicTimeStep())
population_size = 10
max_iterations = 100
step_size_type = 'adaptive'
left_motor = robot.getDevice('left wheel motor')
right_motor = robot.getDevice('right wheel motor')
left_motor.setPosition(float('inf'))
right_motor.setPosition(float('inf'))
ds_front = robot.getDevice('ds_front')
ds_front.enable(timestep)
def distance_to_leader(position):
    return np.sqrt(position[0]**2 + position[1]**2)
def move_robot(direction, speed):
    left_motor.setVelocity(speed * direction)
    right_motor.setVelocity(speed * direction)
robot_position = [0, 0]
```

```python
while robot.step(timestep) != -1:
    front_distance = ds_front.getValue()
    if front_distance > 0.5
        move_robot(random.uniform(-1, 1), 1)
    else:
        leader_position = [0, 0]
        direction_to_leader = leader_position - robot_position
        new_direction, _ = step_size_follow_the_leader(
            distance_to_leader,
            [-1, -1],
            [1, 1],
            population_size,
            max_iterations,
            step_size_type)
        robot_position += new_direction
        move_robot(new_direction, 1)
```

screen videos from the webot simulator shows the results of the simulation using two e-puck robots.

Chapter 6

Conclusion

Beginning with a comprehensive introduction, it delved into an in-depth analysis of the extensive body of literature encompassing both traditional and systematic reviews. The systematic review meticulously examined the diverse array of hardware components essential for realizing functional SR systems, scrutinized the various software architectures, programming languages, platforms, and algorithms that facilitate the emergence of swarm behaviors. This critical analysis identified gaps in existing research and provided insightful suggestions to address these lacunae, such as exploring novel materials, miniaturization techniques, and energy harvesting technologies to expand the capabilities of SR systems, allowing them to operate in increasingly challenging environments for extended periods. Furthermore, the incorporation of advanced artificial intelligence and machine learning techniques was proposed to enhance the intelligence and adaptability of swarm robots. Ultimately, the thesis provided comprehensive answers to the research questions, underscoring the pivotal roles played by both hardware and software in SR. While hardware components are critical for the physical realization of swarm behaviors, software is equally crucial in developing and orchestrating the emergent behaviors that characterize these systems. The thesis also presented an experimental component, commencing with a comparative analysis of centralized and decentralized control systems in SR. While centralized systems offer the potential for optimizing overall swarm behavior due to their global perspective, they are plagued by scalability issues and single points of failure. Conversely, decentralized systems distribute decision-making across all robots, leading to more robust and scalable behaviors that can adapt to dynamic environments. The thesis proposed hybrid models that amalgamate elements of both centralized and decentralized control as a potential solution to mitigate the disadvantages of each approach. Furthermore, the thesis introduced the hardware design employed in the construction of two SR systems, termed ”T-bots,” and elucidated the software design that enabled the robots' functionalities using a master-slave algorithm. Notably, the thesis incorporated a simulation component that tested and evaluated two distinct algorithms: a centralized ”master-slave” algorithm and a decentralized ”follow the leader” algorithm. Through its comprehensive exploration of theoretical and practical aspects, this thesis has made a significant contribution to the field of swarm robotics, providing a solid foundation for future research and advancements in this rapidly evolving domain

References

[1] S. J. Russell and P. Norvig, *Artificial intelligence a modern approach.* London, 4th edition, 2022.

[2] J. Shabbir and T. Anwer, “Artificial intelligence and its role in near future,” *arXiv preprint arXiv:1804.01396*, 2018.

[3] G. Beni, “From swarm intelligence to swarm robotics,” in *International Workshop on Swarm Robotics*, pp. 1–9, Springer, 2004.

[4] E. Şahin, “Swarm robotics: From sources of inspiration to domains of application,” in *International workshop on swarm robotics*, pp. 10–20, Springer, 2004.

[5] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, “Swarm robotics: A perspective on the latest reviewed concepts and applications,” *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[6] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics.* IGI global, 2015.

[7] S. J. Russell and P. Norvig, *Artificial intelligence a modern approach.* London, 2010.

[8] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics.* IGI global, 2015.

[9] M. Schranz, M. Umlauft, M. Sende, and W. Elmenreich, “Swarm robotic behaviors and current applications,” *Frontiers in Robotics and AI*, p. 36, 2020.

[10] Y. Tan and Z.-y. Zheng, “Research advance in swarm robotics,” *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[11] M. Dorigo, G. Theraulaz, and V. Trianni, “Reflections on the future of swarm robotics,” *Science Robotics*, vol. 5, no. 49, p. eabe4385, 2020.

[12] M. Dorigo, G. Theraulaz, and V. Trianni, “Swarm robotics: Past, present, and future [point of view],” *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, 2021.

[13] H. Sheikh, C. Prins, and E. Schrijvers, *Mission AI: The New System Technology*. Springer Nature, 2023.

[14] H. Hamann, *Swarm robotics: A formal approach*, vol. 221. Springer, 2018.

[15] I. Navarro and F. Matía, "An introduction to swarm robotics," *Isrn robotics*, vol. 2013, pp. 1–10, 2013.

[16] L. Bayindir and E. Şahin, "A review of studies in swarm robotics," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 15, no. 2, pp. 115–147, 2007.

[17] N. Nedjah and L. S. Junior, "Review of methodologies and tasks in swarm robotics towards standardization," *Swarm and Evolutionary Computation*, vol. 50, p. 100565, 2019.

[18] M. Dorigo, G. Theraulaz, and V. Trianni, "Swarm robotics: Past, present, and future [point of view]," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, 2021.

[19] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics*. IGI global, 2015.

[20] G. Spezzano, "Special issue "swarm robotics"," 2019.

[21] J. C. Barca and Y. A. Sekercioglu, "Swarm robotics reviewed," *Robotica*, vol. 31, no. 3, pp. 345–359, 2013.

[22] M. Dorigo, G. Theraulaz, and V. Trianni, "Swarm robotics: Past, present, and future [point of view]," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, 2021.

[23] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics*. IGI global, 2015.

[24] Y. Tan and Z.-y. Zheng, "Research advance in swarm robotics," *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[25] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, "Swarm robotics: A perspective on the latest reviewed concepts and applications," *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[26] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, "Swarm robotics: A perspective on the latest reviewed concepts and applications," *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[27] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, “Swarm robotics: A perspective on the latest reviewed concepts and applications,” *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[28] M. Dorigo, G. Theraulaz, and V. Trianni, “Swarm robotics: Past, present, and future [point of view],” *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, 2021.

[29] Y. Tan and Z.-y. Zheng, “Research advance in swarm robotics,” *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[30] E. Bonabeau, “Swarm intelligence,” *A Primer on Multiple Intelligences*, p. 211, 2003.

[31] B. Khaldi and F. Cherif, “An overview of swarm robotics: Swarm intelligence applied to multi-robotics,” *International Journal of Computer Applications*, vol. 126, no. 2, 2015.

[32] G. Beni, “From swarm intelligence to swarm robotics,” in *International Workshop on Swarm Robotics*, pp. 1–9, Springer, 2004.

[33] H. Pabani and A. N. Shire, “Overview of swarm robotics,” *International Journal of Engineering Research and General Science Bd*, vol. 3, pp. 1029–1034, 2020.

[34] Y. Tan and Z.-y. Zheng, “Research advance in swarm robotics,” *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[35] M. N. Sadiku, S. M. Musa, and A. Ajayi-Majebi, *A primer on multiple intelligences*. Springer, 2021.

[36] B. Khaldi and F. Cherif, “An overview of swarm robotics: Swarm intelligence applied to multi-robotics,” *International Journal of Computer Applications*, vol. 126, no. 2, 2015.

[37] M. N. Sadiku, S. M. Musa, and A. Ajayi-Majebi, *A primer on multiple intelligences*. Springer, 2021.

[38] S. Jha, R. G. Casey-Ford, J. S. Pedersen, T. G. Platt, R. Cervo, D. C. Queller, and J. E. Strassmann, “The queen is not a pacemaker in the small-colony wasps polistes instabilis and p. dominulus,” *Animal behaviour*, vol. 71, no. 5, pp. 1197–1203, 2006.

[39] I. Navarro and F. Matía, “An introduction to swarm robotics,” *Isrn robotics*, vol. 2013, pp. 1–10, 2013.

[40] Y. Tan and Z.-y. Zheng, “Research advance in swarm robotics,” *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[41] I. Olaronke, I. Rhoda, I. Gambo, O. Ojerinde, and O. Janet, "A systematic review of swarm robots," 2020.

[42] D. Chakraborty, S. Bhunia, and R. De, "Survival chances of a prey swarm: how the cooperative interaction range affects the outcome," *Scientific Reports*, vol. 10, no. 1, p. 8362, 2020.

[43] C. D. Morin and E. Déziel, "Use of alternative gelling agents reveals the role of rhamnolipids in pseudomonas aeruginosa surface motility," *Biomolecules*, vol. 11, no. 10, p. 1468, 2021.

[44] M. Thrun and A. Ultsch, "Swarm intelligence for self-organized clustering," *Artificial Intelligence*, vol. 290, p. 103237, 01 2020.

[45] P. Lynch, "Emergence: Complex behaviour arising from simple roots," 2019.

[46] F. Lacombe, "Modeling swarm behavior," 2006. Source: University of Calgary.

[47] Y. Tan and Z.-y. Zheng, "Research advance in swarm robotics," *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[48] S. Rahman, I. Sajjad, M. Mansoor, J. Belden, C. Murphy, and T. Truscott, "School formation characteristics and stimuli based modeling of tetra fish," *Bioinspiration Biomimetics*, vol. 15, 07 2020.

[49] Y. Tan and Z.-y. Zheng, "Research advance in swarm robotics," *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[50] Y. Tan and Z.-y. Zheng, "Research advance in swarm robotics," *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[51] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*, pp. 25–34, 1987.

[52] G. W. Flake, *The computational beauty of nature: Computer explorations of fractals, chaos, complex systems, and adaptation.* MIT press, 2000.

[53] S. Garnier, J. Gautrais, and G. Theraulaz, "The biological principles of swarm intelligence," *Swarm intelligence*, vol. 1, pp. 3–31, 2007.

[54] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics.* IGI global, 2015.

[55] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics.* IGI global, 2015.

[56] L. Bayindir and E. Şahin, "A review of studies in swarm robotics," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 15, no. 2, pp. 115–147, 2007.

[57] N. Nedjah and L. S. Junior, "Review of methodologies and tasks in swarm robotics towards standardization," *Swarm and Evolutionary Computation*, vol. 50, p. 100565, 2019.

[58] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics*. IGI global, 2015.

[59] H. Hamann, *Swarm robotics: A formal approach*, vol. 221. Springer, 2018.

[60] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, "Swarm robotics: A perspective on the latest reviewed concepts and applications," *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[61] M. Schranz, M. Umlauft, M. Sende, and W. Elmenreich, "Swarm robotic behaviors and current applications," *Frontiers in Robotics and AI*, p. 36, 2020.

[62] S. Roy, S. Biswas, and S. S. Chaudhuri, "Nature-inspired swarm intelligence and its applications," *International Journal of Modern Education and Computer Science*, vol. 6, no. 12, p. 55, 2014.

[63] Y. Tan, *Handbook of research on design, control, and modeling of swarm robotics*. IGI global, 2015.

[64] P. Gaudiano, B. Shargel, E. Bonabeau, B. T. Clough, *et al.*, "Swarm intelligence: a new c2 paradigm with an application to control of swarms of uavs," in *8th ICCRTS Command and Control Research and Technology Symposium*, vol. 12, 2003.

[65] D. J. Bennet and C. McInnes, "Verifiable control of a swarm of unmanned aerial vehicles," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 223, no. 7, pp. 939–953, 2009.

[66] X. Fan, P. Wu, and M. Xia, "Air-to-ground communications beyond 5g: Uav swarm formation control and tracking," *IEEE Transactions on Wireless Communications*, 2024.

[67] N. R. Gans and J. G. Rogers, "Cooperative multirobot systems for military applications," *Current Robotics Reports*, vol. 2, pp. 105–111, 2021.

[68] W. Johal, Y. Peng, and H. Mi, "Swarm robots in education: A review of challenges and opportunities," *Proceedings of the 8th International Conference on Human-Agent Interaction*, 2020.

[69] A. Ozgur, "Cellulo: Tangible haptic swarm robots for learning," 2018.

[70] I. Olaronke, I. Rhoda, I. Gambo, O. Ojerinde, and O. Janet, "A systematic review of swarm robots," 2020.

[71] W. Johal, Y. Peng, and H. Mi, "Swarm robots in education: A review of challenges and opportunities," in *Proceedings of the 8th International Conference on Human-Agent Interaction*, pp. 272–274, 2020.

[72] P. C. Michael Bartmess, Paul Ernst, "Fast, low-cost swarm robots," 2018. springer2018.

[73] R. Suzuki, C. Zheng, Y. Kakehi, T. Yeh, E. Y.-L. Do, M. D. Gross, and D. Leithinger, "Shapebots: Shape-changing swarm robots," in *Proceedings of the 32nd annual ACM symposium on user interface software and technology*, pp. 493–505, 2019.

[74] V. Trianni and S. Nolfi, "Self-organizing sync in a robotic swarm: A dynamical system view," *IEEE Transactions on Evolutionary Computation*, vol. 13, no. 4, pp. 722–741, 2009.

[75] M. Bakhshipour, M. J. Ghadi, and F. Namdari, "Swarm robotics search & rescue: A novel artificial intelligence-inspired optimization approach," *Applied Soft Computing*, vol. 57, pp. 708–726, 2017.

[76] A. Galstyan, T. Hogg, and K. Lerman, "Modeling and mathematical analysis of swarms of microscopic robots," in *Proceedings 2005 IEEE Swarm Intelligence Symposium, 2005. SIS 2005.*, pp. 201–208, IEEE, 2005.

[77] L. H. Kim, D. S. Drew, V. Domova, and S. Follmer, "User-defined swarm robot control," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2020.

[78] I. Navarro and F. Matía, "An introduction to swarm robotics," *Isrn robotics*, vol. 2013, pp. 1–10, 2013.

[79] D. H. Stolfi and G. Danoy, "Evolutionary swarm formation: From simulations to real world robots," *Engineering Applications of Artificial Intelligence*, vol. 128, p. 107501, 2024.

[80] F. Mahrool, *Research Methodology. A Guide for a Literature Review: A Short Description*. Bod Third Party Titles, 2021.

[81] E. S. Barry, J. Merkebu, and L. Varpio, "State-of-the-art literature review methodology: A six-step approach for knowledge synthesis," *Perspectives on Medical Education*, vol. 11, no. 5, pp. 281–288, 2022.

[82] A. S. Denney and R. Tewksbury, "How to write a literature review," *Journal of criminal justice education*, vol. 24, no. 2, pp. 218–234, 2013.

[83] F. M. Lacey, L. Matheson, and J. Jesson, "Doing your literature review: Traditional and systematic techniques," *Doing Your Literature Review*, pp. 1–192, 2011.

[84] D. Pati and L. N. Lorusso, "How to write a systematic review of the literature," *HERD: Health Environments Research & Design Journal*, vol. 11, no. 1, pp. 15–30, 2018.

[85] Z. H. Ismail and M. G. M. Hamami, "Systematic literature review of swarm robotics strategies applied to target search problem with environment constraints," *Applied Sciences*, vol. 11, no. 5, p. 2383, 2021.

[86] S. Bhalla, P. Kwan, M. Bedekar, R. Phalnikar, and S. Sirsikar, "Proceeding of,"

[87] P. G. F. Dias, M. C. Silva, G. P. Rocha Filho, P. A. Vargas, L. P. Cota, and G. Pessin, "Swarm robotics: A perspective on the latest reviewed concepts and applications," *Sensors*, vol. 21, no. 6, p. 2062, 2021.

[88] B. Udugama, "Review on efficient strategies for coordinated motion and tracking in swarm robotics," *arXiv preprint arXiv:2302.06360*, 2023.

[89] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intelligence*, vol. 7, pp. 1–41, 2013.

[90] E. Sakthivelmurugan, G. Senthilkumar, K. Prithiviraj, and K. R. T. Devraj, "Foraging behavior analysis of swarm robotics system," 2018.

[91] A. Girdhar, S. Zhang, and C. K. M. Lee, "Swarm intelligence and flocking behavior," 2015.

[92] Y. Wei, Z. Liang, and K. Xinchen, "Self-organizing aggregation behavior modeling of swarm robots based on ant colony algorithm," *Computer Simulation*, vol. 32, p. 191, 2020.

[93] M. Edelen, "Swarm intelligence and stigmergy: Robotic implementation of foraging behavior," 2003.

[94] Z. H. Ismail and M. G. M. Hamami, "Systematic literature review of swarm robotics strategies applied to target search problem with environment constraints," *Applied Sciences*, vol. 11, no. 5, p. 2383, 2021.

[95] Z. H. Ismail and M. G. M. Hamami, "Systematic literature review of swarm robotics strategies applied to target search problem with environment constraints," *Applied Sciences*, vol. 11, no. 5, p. 2383, 2021.

[96] B. Udugama, "Review on efficient strategies for coordinated motion and tracking in swarm robotics," *arXiv preprint arXiv:2302.06360*, 2023.

[97] T. Krishnamohan, "A review of the consensus achievement strategies in the context of swarm robotics," *Krishnamohan T. A Review of the Consensus Achievement Strategies in the Context of Swarm Robotics. Mod Intell Times*, vol. 1, p. 1, 2023.

[98] A. Pradhan, M. Boavida, and D. Fontanelli, "A comparative analysis of foraging strategies for swarm robotics using argos simulator," in *2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC)*, pp. 30–35, IEEE, 2020.

[99] N. Nedjah and L. S. Junior, "Review of methodologies and tasks in swarm robotics towards standardization," *Swarm and Evolutionary Computation*, vol. 50, p. 100565, 2019.

[100] V. Bahel, A. Peshkar, and S. Singh, "Swarm intelligence-based systems: A review," in *Proceeding of International Conference on Computational Science and Applications: ICCSA 2019*, pp. 149–156, Springer, 2020.

[101] T. Kano, "Review of interdisciplinary approach to swarm intelligence," *Journal of Robotics and Mechatronics*, vol. 35, no. 4, pp. 890–895, 2023.

[102] I. Prabhudesai, "Swarm robotics based on collective intelligence of social insects : A review," *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT*, 2023.

[103] J. B. Odili, M. N. M. Kahar, and A. Noraziah, "Swarm intelligence optimization algorithms: A review," *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. 10, no. 1-4, pp. 139–142, 2018.

[104] J. Kuckling, "Recent trends in robot learning and evolution for swarm robotics," *Frontiers in Robotics and AI*, vol. 10, p. 1134841, 2023.

[105] Y. Jiang and B.-C. Renner, "Low-cost underwater swarm acoustic localization: a review," *IEEE access*, 2024.

[106] A. M. R. Kabir, D. Inoue, and A. Kakugo, "Molecular swarm robots: recent progress and future challenges," *Science and technology of advanced materials*, vol. 21, no. 1, pp. 323–332, 2020.

[107] M. Abdelkader, S. Güler, H. Jaleel, and J. S. Shamma, "Aerial swarms: Recent applications and challenges," *Current robotics reports*, vol. 2, pp. 309–320, 2021.

[108] W. Johal, Y. Peng, and H. Mi, "Swarm robots in education: A review of challenges and opportunities," in *Proceedings of the 8th International Conference on Human-Agent Interaction*, pp. 272–274, 2020.

[109] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intelligence*, vol. 7, pp. 1–41, 2013.

[110] M. Dorigo, G. Theraulaz, and V. Trianni, "Swarm robotics: Past, present, and future [point of view]," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, 2021.

[111] I. Olaronke, I. Rhoda, I. Gambo, O. Ojerinde, and O. Janet, "A systematic review of swarm robots," 2020.

[112] C. Calderón-Arce, J. C. Brenes-Torres, and R. Solis-Ortega, "Swarm robotics: Simulators, platforms and applications review," *Computation*, vol. 10, no. 6, p. 80, 2022.

[113] G. Cherry, A. Boland, and R. Dickson, "Doing a systematic review: A student s guide," 2023.

[114] J. P. Kelly and I. H. Osman, *Meta-heuristics: theory and applications.* Kluwer Norwell, 1996.

[115] C.-W. Tsai and M.-C. Chiang, *Handbook of metaheuristic algorithms: from fundamental theories to advanced applications.* Elsevier, 2023.

[116] H. T. Jongen, K. Meer, and E. Triesch, *Optimization theory.* Springer Science & Business Media, 2007.

[117] E. Şahin, S. Girgin, L. Bayindir, and A. E. Turgut, *Swarm robotics.* Springer, 2008.

[118] H. Tello-Rodríguez and L. Torres-Treviño, "Characterization of environment using the collective perception of a smart swarm robotics based on data from local sensors," in *Smart Technology: First International Conference, MTYMEX 2017, Monterrey, Mexico, May 24-26, 2017, Proceedings*, pp. 133–140, Springer, 2018.

[119] E. Şahin, "Swarm robotics: From sources of inspiration to domains of application," in *International workshop on swarm robotics*, pp. 10–20, Springer, 2004.

[120] N. Nedjah and L. S. Junior, "Review of methodologies and tasks in swarm robotics towards standardization," *Swarm and Evolutionary Computation*, vol. 50, p. 100565, 2019.

[121] É. Villemure, P. Arsenault, G. Lessard, T. Constantin, H. Dubé, L.-D. Gaulin, X. Groleau, S. Laperrière, C. Quesnel, and F. Ferland, "Swarmus: An open hardware and software on-board platform for swarm robotics development," *arXiv preprint arXiv:2203.02643*, 2022.

[122] M. Salman, A. Ligot, and M. Birattari, "Concurrent design of control software and configuration of hardware for robot swarms under economic constraints," *PeerJ Computer Science*, vol. 5, p. e221, 2019.

[123] M. Patil, T. Abukhalil, S. Patel, and T. Sobh, "Ub robot swarm—design, implementation, and power management," in *2016 12th IEEE International Conference on Control and Automation (ICCA)*, pp. 577–582, IEEE, 2016.

[124] M. Salman, A. Ligot, and M. Birattari, "Concurrent design of control software and configuration of hardware for robot swarms under economic constraints," *PeerJ Computer Science*, vol. 5, p. e221, 2019.

[125] M. Salman, A. Ligot, and M. Birattari, "Concurrent design of control software and configuration of hardware for robot swarms under economic constraints," *PeerJ Computer Science*, vol. 5, p. e221, 2019.

[126] M. Patil, T. Abukhalil, and T. Sobh, "Hardware architecture review of swarm robotics system: Self-reconfigurability, self-reassembly, and self-replication," *International Scholarly Research Notices*, vol. 2013, 2013.

[127] B. Shang, *Hardware variation in robotic swarm and behavioural sorting with swarm chromatography.* PhD thesis, University of Southampton, 2017.

[128] N. Nedjah and L. S. Junior, "Review of methodologies and tasks in swarm robotics towards standardization," *Swarm and Evolutionary Computation*, vol. 50, p. 100565, 2019.

[129] A. Özgür, S. Lemaignan, W. Johal, M. Beltran, M. Briod, L. Pereyre, F. Mondada, and P. Dillenbourg, "Cellulo: Versatile handheld robots for education," in *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, pp. 119–127, 2017.

[130] M. Patil, T. Abukhalil, S. Patel, and T. Sobh, "Ub robot swarm—design, implementation, and power management," in *2016 12th IEEE International Conference on Control and Automation (ICCA)*, pp. 577–582, IEEE, 2016.

[131] M. Le Goc, L. H. Kim, A. Parsaei, J.-D. Fekete, P. Dragicevic, and S. Follmer, "Zooids: Building blocks for swarm user interfaces," in *Proceedings of the 29th annual symposium on user interface software and technology*, pp. 97–109, 2016.

[132] V. Costa, M. Duarte, T. Rodrigues, S. M. Oliveira, and A. L. Christensen, "Design and development of an inexpensive aquatic swarm robotics system," in *Oceans 2016-Shanghai*, pp. 1–7, IEEE, 2016.

[133] P. C. Michael Bartmess, Paul Ernst, "Fast, low-cost swarm robots," 2018. springer2018.

[134] F. Arvin, J. C. Murray, L. Shi, C. Zhang, and S. Yue, "Development of an autonomous micro robot for swarm robotics," in *2014 IEEE International Conference on Mechatronics and Automation*, pp. 635–640, IEEE, 2014.

[135] S. Mintchev, E. Donati, S. Marrazza, and C. Stefanini, "Mechatronic design of a miniature underwater robot for swarm operations," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2938–2943, IEEE, 2014.

[136] N. Moustafa, A. Gálvez, and A. Iglesias, "A general-purpose hardware robotic platform for swarm robotics," in *Intelligent Distributed Computing XII*, pp. 259–271, Springer, 2018.

[137] Y. Mulgaonkar, G. Cross, and V. Kumar, "Design of small, safe and robust quadrotor swarms," in *2015 IEEE international conference on robotics and automation (ICRA)*, pp. 2208–2215, IEEE, 2015.

[138] D. Pickem, P. Glotfelter, L. Wang, M. Mote, A. Ames, E. Feron, and M. Egerstedt, "The robotarium: A remotely accessible swarm robotics research testbed," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1699–1706, IEEE, 2017.

[139] D. A. Patil, M. Y. Upadhye, F. Kazi, and N. Singh, "Multi robot communication and target tracking system with controller design and implementation of swarm robot using arduino," in *2015 International Conference on Industrial Instrumentation and Control (ICIC)*, pp. 412–416, IEEE, 2015.

[140] M. T. M. Triveni, L. Lakshmi, and A. Lalitha, "Design and implement multi robot for tar," 2020.

[141] Ç. A. Demir, "Design of a low-costs warm robotic system for flocking," Master's thesis, Middle East Technical University, 2019.

[142] J. McLurkin, A. McMullen, N. Robbins, G. Habibi, A. Becker, A. Chou, H. Li, M. John, N. Okeke, J. Rykowski, *et al.*, "A robot system design for low-cost multi-

robot manipulation," in *2014 IEEE/RSJ international conference on intelligent robots and systems*, pp. 912–918, IEEE, 2014.

[143] J. Y. Kim, Z. Kashino, T. Colaco, G. Nejat, and B. Benhabib, "Design and implementation of a millirobot for swarm studies–mroberto," *Robotica*, vol. 36, no. 11, pp. 1591–1612, 2018.

[144] S. P. Kumar, A. Ravindiran, S. Meganathan, N. O. Roberts, and N. Anbarasi, "Swarm robot materials handling paradigm for solar energy conservation," *Materials Today: Proceedings*, vol. 46, pp. 3924–3928, 2021.

[145] F. Bonnet, Y. Kato, J. Halloy, and F. Mondada, "Infiltrating the zebrafish swarm: design, implementation and experimental tests of a miniature robotic fish lure for fish–robot interaction studies," *Artificial Life and Robotics*, vol. 21, pp. 239–246, 2016.

[146] P. A. Rezeck, H. Azpurua, and L. Chaimowicz, "Hero: An open platform for robotics research and education," in *2017 Latin American Robotics Symposium (LARS) and 2017 Brazilian Symposium on Robotics (SBR)*, pp. 1–6, IEEE, 2017.

[147] B. Shang, R. Crowder, and K.-P. Zauner, "Simulation of hardware variations in swarm robots," in *2013 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 4066–4071, IEEE, 2013.

[148] A. Abuelhaija, A. Jebrein, and T. Baldawi, "Swarm robotics: Design and implementation.," *International Journal of Electrical & Computer Engineering (2088-8708)*, vol. 10, no. 2, 2020.

[149] M. N. Jisu Elsa Jacob, *Simplified Robotics: An Illustrative Guide to Learn Fundamentals of Robotics, Including Kinematics, Motion Control, and Trajectory Planning.* India: BPB publications, india, 2022.

[150] B. Shang, *Hardware variation in robotic swarm and behavioural sorting with swarm chromatography.* PhD thesis, University of Southampton, 2017.

[151] É. Villemure, P. Arsenault, G. Lessard, T. Constantin, H. Dubé, L.-D. Gaulin, X. Groleau, S. Laperrière, C. Quesnel, and F. Ferland, "Swarmus: An open hardware and software on-board platform for swarm robotics development," *arXiv preprint arXiv:2203.02643*, 2022.

[152] R. Arrick and N. Stevenson, *Robot building for dummies.* John Wiley & Sons, 2003.

[153] N. Moustafa, A. Gálvez, and A. Iglesias, "A general-purpose hardware robotic platform for swarm robotics," in *Intelligent Distributed Computing XII*, pp. 259–271, Springer, 2018.

[154] R. S. Pressman, *Software engineering: a practitioner's approach.* Palgrave macmillan, 2005.

[155] M. Salman, A. Ligot, and M. Birattari, "Concurrent design of control software and configuration of hardware for robot swarms under economic constraints," *PeerJ Computer Science*, vol. 5, p. e221, 2019.

[156] M. Rubenstein, A. Cornejo, and R. Nagpal, "Programmable self-assembly in a thousand-robot swarm," *Science*, vol. 345, no. 6198, pp. 795–799, 2014.

[157] G. Francesca, M. Brambilla, A. Brutschy, L. Garattoni, R. Miletitch, G. Podevijn, A. Reina, T. Soleymani, M. Salvaro, C. Pinciroli, *et al.*, "Automodechocolate: automatic design of control software for robot swarms," *Swarm Intelligence*, vol. 9, pp. 125–152, 2015.

[158] K. Hasselmann, *Advances in the automatic modular design of control software for robot swarms: Using neuroevolution to generate modules.* PhD thesis, PhD thesis. Brussels, Belgium: Université libre de Bruxelles, 2023.

[159] Y. Zhang, L. Zhang, H. Wang, F. E. Bustamante, and M. Rubenstein, "Swarmtalk-towards benchmark software suites for swarm robotics platforms," in *Proceedings of the 19th International Conference on Autonomous Agents and MultiAgent Systems*, pp. 1638–1646, 2020.

[160] C. Pinciroli and G. Beltrame, "Swarm-oriented programming of distributed robot networks," *Computer*, vol. 49, no. 12, pp. 32–41, 2016.

[161] G. Francesca and M. Birattari, "Automatic design of robot swarms: achievements and challenges," *Frontiers in Robotics and AI*, vol. 3, p. 29, 2016.

[162] E. M. de Andrade, A. C. Fernandes, and J. S. Sales, "Pyswarming: a research toolkit for swarm robotics," *Journal of Open Source Software*, vol. 8, no. 89, p. 5647, 2023.

[163] Á. Madridano, A. Al-Kaff, P. Flores, D. Martín, and A. de la Escalera, "Software architecture for autonomous and coordinated navigation of uav swarms in forest and urban firefighting," *Applied Sciences*, vol. 11, no. 3, p. 1258, 2021.

[164] I. Akkaya, S. Emoto, and E. A. Lee, "Pilot: An actor-oriented learning and optimization toolkit for robotic swarm applications," in *International Workshop on Robotic Sensor Networks*, 2015.

[165] K. A. Stolleis, "Swarming robot design, construction and software implementation," tech. rep., 2014.

[166] M. Brambilla, A. Brutschy, M. Dorigo, and M. Birattari, "Property-driven design for robot swarms: A design method based on prescriptive modeling and model

checking," *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, vol. 9, no. 4, pp. 1–28, 2014.

[167] M. Gansari and C. Buiu, "Software system integration of heterogeneous swarms of robots," *Journal of Control Engineering and Applied Informatics*, vol. 19, no. 3, pp. 49–57, 2017.

[168] M. Chamanbaz, D. Mateo, B. M. Zoss, G. Tokić, E. Wilhelm, R. Bouffanais, and D. K. Yue, "Swarm-enabling technology for multi-robot systems," *Frontiers in Robotics and AI*, vol. 4, p. 12, 2017.

[169] L. E. Parker, D. Rus, and G. S. Sukhatme, "Multiple mobile robot systems," *Springer handbook of robotics*, pp. 1335–1384, 2016.

[170] G. Francesca, M. Brambilla, A. Brutschy, L. Garattoni, R. Miletitch, G. Podevijn, A. Reina, T. Soleymani, M. Salvaro, C. Pinciroli, *et al.*, "An experiment in automatic design of robot swarms: Automode-vanilla, evostick, and human experts," in *Swarm Intelligence: 9th International Conference, ANTS 2014, Brussels, Belgium, September 10-12, 2014. Proceedings 9*, pp. 25–37, Springer, 2014.

[171] J. Kuckling, A. Ligot, D. Bozhinoski, and M. Birattari, "Behavior trees as a control architecture in the automatic modular design of robot swarms," in *International conference on swarm intelligence*, pp. 30–43, Springer, 2018.

[172] K. Hasselmann, F. Robert, and M. Birattari, "Automatic design of communication-based behaviors for robot swarms," in *Swarm Intelligence: 11th International Conference, ANTS 2018, Rome, Italy, October 29–31, 2018, Proceedings 11*, pp. 16–29, Springer, 2018.

[173] A. Dimakos, D. Woodhall, and S. Asif, "A study on centralised and decentralised swarm robotics architecture for part delivery system," *arXiv preprint arXiv:2403.07635*, 2024.

[174] J. Hu, A. Bruno, D. Zagieboylo, M. Zhao, B. Ritchken, B. Jackson, J. Y. Chae, F. Mertil, M. Espinosa, and C. Delimitrou, "To centralize or not to centralize: A tale of swarm coordination," *arXiv preprint arXiv:1805.01786*, 2018.

[175] I. Navarro, E. Di Mario, and A. Martinoli, "Distributed vs. centralized particle swarm optimization for learning flocking behaviors," in *Proceedings of the European Conference on Artificial Life 2015*, pp. 302–309, The MIT Press, 2015.

[176] M. Lee, A. Alvarez, F. De Pellegrini, B. Prabhakaran, and I. Chlamtac, "Robotrak: a centralized real-time monitoring, control, and coordination system for robot swarms," in *1st International ICST Conference on Robot Communication and Coordination*, 2010.

[177] "Heavy duty caster wheels."

[178] "L298n motor driver."

[179] "Ir sensors."

[180] P. Singh and R. Kottath, "A step-size follow-the-leader optimization algorithm with an improved step parameters," *Decision Analytics Journal*, vol. 9, p. 100360, 2023.

[181] P. Singh and R. Kottath, "A step-size follow-the-leader optimization algorithm with an improved step parameters," *Decision Analytics Journal*, vol. 9, p. 100360, 2023.