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Jawad Naveed Yasin

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I dedicate this thesis to my parents
Sweetest mother Fauzia Yasin and greatest friend my dad
Prof. Muhammad Mehboob Yasin, for without them
none of this was possible

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ABSTRACT

Formation maintenance and collision avoidance are two of the key factors in swarm robotics. The demand for autonomous fleets of robots is ever increasing from manufacturing to product deliveries to surveillance to mapping and so on. Moreover, for resource constrained autonomous robots, such as UAVs and UGVs, energy-efficiency is very vital due to their limited batteries. Therefore formation maintenance and collision avoidance developed for such robots need to be energy-efficient. Integration between these two approaches needs to be performed systematically. The experimental analysis of the proposed approaches presented in this thesis target two main branches: 1) action based and 2) perception based energy consumption in a swarm of robots. In the first branch, there are two different paths: *i)* optimal formation morphing: the main goal is to the optimize the reformation process from the highest level of agitation of the swarm, i.e., maximum disturbance in the formation shape and *ii)* congestion minimization: the main goal here is to find an optimal solution for distribution of the swarm into sub-swarms to minimize the delays due to over population of the agents while bypassing the obstacles. In the second branch, i.e., perception based energy consumption, the main goal is to increase the mission life on a single charge by injecting the adaptive consciousness into the agents so they can turn off their ranging sensors and navigate while listening to their leader. For formation collision co-awareness, we systematically integrated the methodologies by designing a multi-priority control and utilized the non-rigid mapping scheme of thin-plate splines technique to minimize the deformation caused by obstacle avoidance. For congestion-aware morphing and avoidance maneuvers, we discuss how the delays caused by over population can be minimized with local sense and avoid approach. The leader, upon detection of obstacles, pre-estimates the optimal configuration, i.e., number of agents in the sub-swarms, and divides the swarm as such. We show the efficiency of the proposed approach experimentally.

KEYWORDS: swarm intelligence, formation maintenance, collision avoidance, energy-efficiency

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TIIVISTELMÄ

Parvirobotiikassa muodostelman ylläpitäminen ja törmäysten välttäminen ovat avainasemassa. Autonomisten robottiparvien kysyntä on jatkuvasti kasvussa niin teollisuudessa, tuotetoimituksessa, valvonnassa ja kartoituksessa kuin muillakin toimialoilla. Lisäksi resursseiltaan rajallisten autonomisten robottien, kuten miehittämättömien ilma- ja vesialusten, energiatehokkuus on keskeisen tärkeää alusten rajallisista akkukapasiteeteista johtuen, minkä johdosta kyseisille roboteille kehitettävissä muodostelman ylläpito- ja törmäyksenestojärjestelmissä on kiinnitettävä erityistä huomiota ratkaisun energiatehokkuuteen. Näiden kahden toiminnan integrointi on suoritettava järjestelmällisesti.

Tässä väitöskirjassa esitettyjen lähestymistapojen kokeellinen analyysi jakaantuu kahteen päähaaraan: 1) toimintaan perustuva ja 2) havaintaan perustuva energiakulutuksen optimointi robottiparvessa. Ensimmäinen päähaara jakautuu kahteen alihaaraan: *i)* parvimuodostelman optimaalinen muodonmuutos: päätavoitteena on optimoida uudelleenmuodostusprosessi parven korkeimmalta agitaatiotasolta käsin, kuten muodostelman hajottua maksimaalisen häiriön seurauksena sekä *ii)* ruuhkautumisen minimointi: päätavoitteena on löytää optimaalinen ratkaisu parven osaparviin jakautumista varten, jolloin esteitä ohittaessa pystytään minimoimaan reittien ruuhkautumisesta johtuvat viivästykset.

Toisessa päähaarassa, havaintaan perustuvassa energiankulutuksen optimoinnissa, päätavoitteena on yksittäisellä akunlatauksella saavutettavan tehtäväkeston lisääminen. Tähän pyritään injektoimalla agentteihin adaptiivinen tietoisuus, jota hyödyntäen ne pystyvät navigoimaan ilman mittausantureja johtajansa välittämän tiedon avulla.

Muodostelman törmäykseneston yhteistietoisuuden saavuttamiseksi esitetyt metodologiat integroidaan suunnittelemalla usean prioriteettitason ohjausjärjestelmä ja hyödyntämällä Thin Plate Spline - menetelmään perustuvaa kartoitusmetodia esteiden vältön aiheuttamien parven muodonmuutosten minimoimiseksi.

Ruuhkatietoisiin muodonmuutos- ja väistämismenetelmiin liittyen tarkastellaan, miten reittien ruuhkautumista voidaan minimoida lokaalia Sense and Avoid - lähestymistapaa hyödyntäen. Tällöin havaitessaan esteitä parven johtaja arvioi ennakkoon optimaaliset järjestäytymistoimenpiteet, kuten agenttien määrät aliparvissa, ja jakaa parven arvionsa perusteella. Esitetyn ratkaisun tehokkuutta tarkastellaan kokeellisesti.

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Finally, I would like to show my deep gratitude to my sisters and brothers for their great support throughout my life and in this journey. I would like to thank God, for keeping me on the right path and helping me through all the difficulties in my life.

01.08.2022

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Table of Contents

Abbreviations

d	Distance
DFRPSR	Dynamic Formation Reshaping based on Point Set Registration
D_i	Distance of each drone's current position to the estimated avoidance location
Δd_{oi}	Distance covered by the obstacle
D_R	Detection Range
d_{ti}	Distance between the agent and the obstacle at current time
d_{ti-1}	Distance between the agent and the obstacle at previous interval
d_{ui}	Distance travelled by the agent
$\overline{d}$	Calculated average distance of the drones/agents from each other
EFMCA	Energy-efficient Formation morphing for Collision Avoidance
E_{TPS}	Energy function of TPS
FoV	Field of View
$f(v_i)$	Mapping function
G_i	Group set
IOAA	Improved Obstacle Avoidance Algorithm
IR	Infrared
J	Number of drones
λ	Scaling factor
LiDAR	Light Detection And Ranging
MAS	Multi-Agent Systems

MRS	Multi-Robot Systems
Obj	Obstacle/object
PSR	Point-Set Registration
r_A	Position vector of the agent
R_C	Collision radius
r_{Obj}	Position vector of the obstacle
TPS	Thin-Plate Spline
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
US	UltraSonic
UV	Unmanned Vehicle
v_i	Point in model
v_o	Calculated velocity of the obstacle
x_i	Point in a scene
τ	Overall time
v_i	Velocity of the drones
θ_{obj}	Angle at which the object is detected

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, J. Plosila. Unmanned Aerial Vehicles (UAVs): Collision Avoidance Systems and Approaches. IEEE Access, 2020; Vol. 8: pp. 105139 – 105155.

II **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, J. Plosila. Low-cost Ultrasonic based Object Detection and Collision Avoidance Method for Autonomous Robots. International Journal of Information Technology, 2021; Vol. 13, pp. 97 – 107.

III **J.N. Yasin**, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, J. Plosila. Formation Maintenance and Collision Avoidance in a Swarm of Drones. in Proceedings of the 2019 3rd International Symposium on Computer Science and Intelligent Control (ISCSIC 2019), ACM 2019; Art. 1: pp. 1 – 6, Netherlands.

IV **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, M.M. Yasin, J. Plosila. Night Vision Obstacle Detection and Avoidance Based on Bio-Inspired Vision Sensors. IEEE Sensors, 2020; pp. 1 – 4, Netherlands.

V **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, M.M. Yasin, J. Plosila. Dynamic Formation Reshaping Based on Point Set Registration in a Swarm of Drones. Future of Information and Communication Conference (FICC 2021), 2021; Advances in Intelligent Systems and Computing, Vol 1363: pp. 577 – 588, Canada.

VI **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, M.M. Yasin, J. Plosila. Energy-efficient Formation Morphing for Collision Avoidance in a Swarm of Drones. IEEE Access, 2020; Vol. 8: pp. 170681 – 170695.

VII **J.N. Yasin**, S.A.S. Mohamed, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, J. Plosila. Navigation of Autonomous Swarm of Drones using Translational Coordinates. in Springer 18th International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS 2020), 2020; pp. 353 – 362, Italy.

VIII **J.N. Yasin**, H. Mahboob, M.H. Haghbayan, M.M. Yasin, and J. Plosila. Energy-efficient Navigation of an Autonomous Swarm with Adaptive Consciousness. Remote Sensing, 2021; Vol. 13: Issue. 6, Art. 1059: pp. 1 – 17.

IX **J.N. Yasin**, H. Mahboob, M.H. Haghbayan, M.M. Yasin, and J. Plosila. Cellular Formation Maintenance and Collision Avoidance Using Centroid-Based Point Set Registration in a Swarm of Drones. Intelligent Systems Conference (IntelliSys), 2021.

X **J.N. Yasin**, M.H. Haghbayan, M.M. Yasin, and J. Plosila. Swarm Formation Morphing for Congestion-Aware Collision Avoidance. Heliyon, Vol. 7: Issue. 8, 2021.

The list of original publications have been reproduced with the permission of the copyright holders.

List of other relevant publications by the author that are not included in this thesis:

- **J.N. Yasin**, H. Mahboob, S. Jokinen, M.H. Haghbayan, M.M. Yasin, J. Plosila. Partial Swarm SLAM for Intelligent Navigation. in Springer 20th International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS 2022), Italy

- S.A.S. Mohamed, **J.N. Yasin**, M.H. Haghbayan, J. Heikkonen, H. Tenhunen, and J. Plosila. Asynchronous Corner Tracking Algorithm based on Lifetime of Events for DAVIS Cameras. in 15th International Symposium on Visual Computing (ISVC 2020), USA.

- S.A.S. Mohamed, **J.N. Yasin**, M.H. Haghbayan, J. Heikkonen, A. Miele, and J. Plosila. Dynamic Resource-aware Corner Detection for Bio-inspired Vision Sensors. in 25th International Conference on Pattern Recognition (ICPR 2020), Italy.

- S.A.S. Mohamed, **J.N. Yasin**, M.H. Haghbayan, J. Heikkonen, and J. Plosila, DBA-Filter: A Dynamic Background Activity Noise Filtering Algorithm for Event cameras. in Proc. of Computing Conference 2021 (CC 2021), UK.

1 Introduction

Unmanned vehicles (UVs) promise significant potential in various practical applications, especially in the case of multi-robot systems (MRS), where several UVs coordinate or cooperate together to achieve a certain task. Due to the advantages of utilizing or deploying multiple unmanned autonomous vehicles in a swarm, a notable amount of researchers have their focus turned towards swarming in multi-robot systems. Among various areas in MRS, formation maintenance, also commonly referred to as formation control, and collision avoidance are the two most important and actively studied areas [1]. UVs can be classified as Unmanned Ground Vehicle (UGV), Unmanned Aerial Vehicle (UAV), and Unmanned Surface Vehicle (USV), where UGVs are the vehicles that maneuver on the ground, UAVs are the vehicles that operate in the air, and USVs are the ones that operate on the surface of the water. These can be controlled either manually, i.e., remotely controlled via a pilot, or can be semi-autonomous, or fully-autonomous [2]. Due to the relatively small size, UVs (especially UAVs) have uses in various practical applications, including but not limited to military, surveying, search and rescue, hazardous places or disaster-hit areas where the human approach is either difficult or can pose danger to human life. The level of autonomy in most of the present-day UVs is low due to the limitations because of their limited payload capacity. Further, as a trade-off to their small sizes, they have limited capacity for carrying payloads, such as the battery, computational units, and sensors, and hence very limited mission life [3; 4]. To help cover the shortcomings, UVs, if deployed in fleets, can cover a wider area and in coordination may be able to perform tasks more effectively.

For multiple UVs or agents to be deployed in the form of fleets or better known as a swarm, a state-of-the-art formation maintenance methodology needs to be in place for the agents to carry out the tasks and maintain the formation safely. The main focus of the formation control/maintenance methods is to guide the agents in the swarm to maintain a certain formation by generating the control velocities [5]. Extensive research is being focused on the development of better formation control methodologies in order to assist the agents to maintain the desired formation shapes dynamically while navigating towards their destination. Formation maintenance methodologies can be generalized into the following three approaches: 1) leader-follower based, where the autonomous agents follow either a dedicated leader or a dynamically elected leader by maintaining their velocities and positions according to the leader to maintain the desired formation shape as close as possible [6]; 2) virtual structure based, in which the whole formation is considered a single agent and is navigated accordingly based on the scenario at hand [7; 8]; 3) behavior based, where the agents select one of the various pre-defined strategies depending on the situation [9; 10].

UVs, deployed in swarms, are gaining tremendous popularity in various and diverse application areas, such as military, search and rescue, surveying, patrolling, commercial use, and research purposes [11]. One way to keep agents maintain the formation shape is to control them from a central server, however, it may not be an optimal solution, especially in scenarios where the communication channels may get cut off or are not available, such as in disaster-hit areas or swarms in military missions. Furthermore, for search and rescue in disaster-hit areas or military purposes, the agents may have to function with no-prior map information as well. In such situations, it is very critical for the agents to be able to make decisions locally and quickly. Therefore, local formation maintenance and robust collision avoidance systems need to be on board all agents to enable the swarm to function safely. In order to tackle these issues, the leader-follower based formation maintenance approach seems most optimal as this methodology is easily scalable and all the agents function individually and autonomously in this methodology. Moreover, for the agents to be able to detect any obstacles/objects and react to avoid colliding with them, the ability to locally sense and avoid is vital. Sense and avoid ability ensures the agile and safe movement of the agents even in complex environments. Since the agents have limited resources, the development of energy-efficient algorithms/methodologies has been the focal point in the research community to guarantee longer mission life on a single charge. The energy efficiency discussed in this thesis is focused on finding the optimal solution for minimizing the disturbance caused by the presence of obstacles in the vicinity of the swarm. Another interesting area discussed in this thesis is to reduce energy consumption due to the use of ranging sensors for local and sense and avoid. Moreover, another different aspect and a new idea of making the system efficient by minimizing the delays due to congestion caused by the agents in the swarm. This congestion happens when the agents navigate towards the same narrow passage for their personal efficient solution. Whereas in the congestion-aware solution, the overall efficiency of the swarm is considered, this may mean some of the agents get a distance penalty meaning higher individual consumption.

1.1 Research Questions

The naive idea to tackle the issue of formation maintenance with collision avoidance is to prioritize one over the other. However, the challenge raises with which module to prioritize over the other and how to optimally do this. The other challenge is to keep the energy consumption as low as possible to make the system energy efficient.

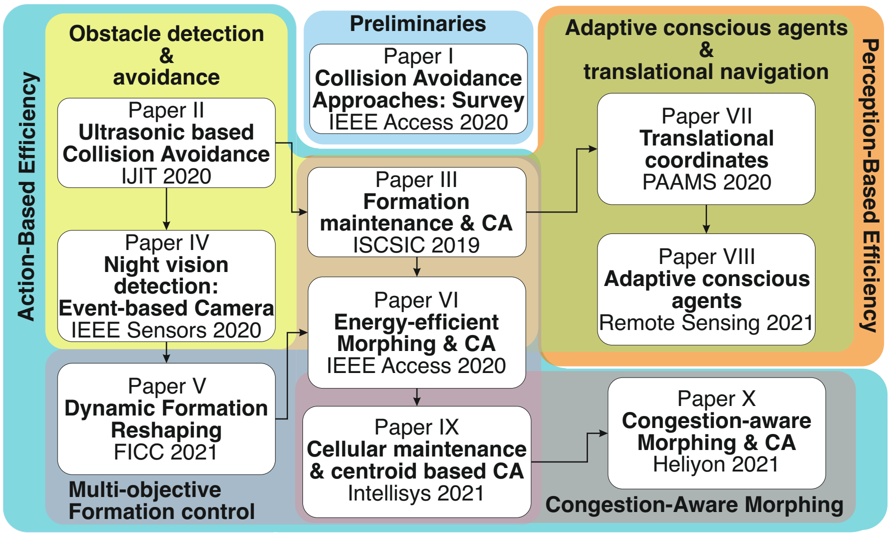


Figure 1. General outline of the works included in this dissertation. Different colors are used for each category

Energy consumption can be reduced by refining various factors in the agent's functionality as well as in the swarm. Our focus is to reduce the consumption due to the disturbance caused by collision avoidance. The overall goal is to investigate and develop methods to make the system more efficient as a whole. The following main research questions will be addressed:

- *Formation collision co-awareness*: is it possible to introduce a systematic integration of formation maintenance with collision avoidance to achieve an adaptive switching between the modules, especially when agents can accelerate and decelerate according to the situation at hand?
- *Adaptive conscious agents: utilizing translational coordinates based navigation*: is it possible to further minimize the energy consumption of the agents in the swarm to achieve longer mission life on a single charge?
- *Congestion aware collision avoidance*: is it possible to optimize over population issue, that occurs due to the agent's individual optimized solutions, to attain a solution that is optimal for the swarm as a whole?

1.2 Contributions

This thesis answers the above questions by investigating them by taking into consideration different existing aspects and constraints in the current design of the systems. The general outline of the works accomplished supported by the publications in this thesis while dealing with formation maintenance and collision avoidance is given in Figure 1. The publications that are included in this thesis are highlighted in the figure. The main tracks to tackle the mentioned issues are *multi-objective formation maintenance and collision avoidance strategy*, *agents with adaptive consciousness*, and *congestion aware strategy*. The energy efficiency aspect considered in the thesis covers two branches: perception based and action based efficiency.

As a preliminary study, a comprehensive literature survey has been performed to investigate and understand the state-of-the-art collision avoidance methodologies (Paper I), this is mentioned in the ”Preliminaries” box of Figure 1. Action based energy efficiency is covered in two parts: 1) Papers III, V, and VI cover the agitation minimization in the agents that occurs due to the presence of obstacles in their trajectory; 2) Papers IX and X cover the congestion reduction in the swarm when passing through the available gaps between the obstacles. Perception based energy efficiency is covered in Papers VII and VIII.

The objective of this thesis is the development of energy-efficient approaches for a swarm of UAVs. A comprehensive collision avoidance approach that is applicable for single, as well as multiple agents, is developed and deployed onto a mobile robot, equipped with an ultrasonic sensor, for testing purposes. This is presented and discussed in Paper II. Furthermore, another experiment performed was with the data-set acquired from an event-based camera as discussed in Paper IV.

Formation maintenance: For the development of the formation maintenance algorithm, the leader-follower based maintenance approach is used. Firstly, the development of the formation maintenance approach is integrated with the developed collision avoidance methodology. The integration of collision avoidance with formation maintenance algorithm is critical, as there can be a competition between both methodologies especially when obstacles are encountered. When formation maintenance takes priority, under what circumstances collision avoidance takes priority, and in what scenarios do both methodologies work concurrently while being aware of each other, i.e., feeding off each other's feedback. After this agile development, the other critical feature, i.e., fault tolerance, is added to the overall system. When dealing with a leader-follower based maintenance approach, fault tolerance in case of losing communication with the leader is vital since the whole swarm is dependent on the leader. In order to handle this, we gave the role of temporary leadership to all the agents in the swarm by making the leader as the global leader and its following agents as the secondary leaders for their followers. The results and discussions on this are presented in Paper III. Later, in Paper V the formation morphing technique is developed to tackle the efficient morphing of the formation shape from one shape to another while navigating through the obstacles. After that, in Paper VI these techniques are further enhanced, by making the system energy efficient, by applying the Thin-plate splines technique for maintaining the formation in an open space, and also for bringing the agents back into the desired formation shape from the point of highest disturbance, i.e., after collision avoidance phase.

Perception based efficiency: Ranging sensors equipped on the autonomous agents have a typical consumption rating. These sensors will consume a certain amount of power per unit of time. Although the companies are striving on making their commercial sensors as power efficient as possible, still there needs to be some other mechanism onboard to make the system more efficient due to the limited amount of batteries and resources mobile robots have. This serves as the main reason for our investigation presented in Paper VII. In the presented technique, the leader keeps transmitting its own coordinates along with the coordinates of any detected obstacles in the vicinity. Follower agents, upon receiving the information, translate the coordinates according to their own respective locations to triangulate the location of the obstacles with their respective locations. Translated coordinates are cross-checked by the leader for any significant errors. If the cross-check results in an error higher than the defined threshold level, the leader signals the follower to turn on its sensors to perform active collision avoidance. Later the mentioned approach is further improved by injecting adaptive consciousness in the agents. In this case, the followers upon translating the coordinates, can themselves decide when they have to turn their ranging sensors on. In case of a dynamic obstacle in the vicinity, the follower agents examine the current translated coordinates reading with the past readings to realize that the obstacle is moving. Moreover, by performing the necessary calculations, the follower can, without turning its sensors on, also determine the approximate velocity of the detected obstacle and the direction it is moving in. Detailed discussions on this approach are addressed in Paper VIII.

Congestion awareness: When a swarm navigating in a certain formation shape encounters obstacles, it can either bypass them by keeping the formation shape and choosing a single trajectory that allows the swarm to evade the obstacles while keeping the formation shape or it can navigate through the available gaps between the obstacles by breaking the formation. The first option may not be the most optimal one, as some or most of the agents may have to travel an unnecessarily long distance to bypass the obstacles. However, in case of breaking the formation and navigating the agents through the available gaps between the obstacles, the traditional methods can be further enhanced to make the system more efficient. In the case of leader-follower based approaches and shortest path avoidance approaches, all the agents will navigate towards their respective leaders or the shortest paths respectively. Both of these approaches can lead to overpopulation at those routes and cause unnecessary delays, increasing the time it takes for the agents to bypass the obstacles, and increasing the energy consumption of the agents and hence of the swarm as a result. This serves as the main motivation behind our quest for a congestion aware technique. In this technique, the leader, upon detection of the obstacles, performs an estimation calculation to identify the optimal number of agents for each available gap between the obstacles to minimize the congestion delays. Based on these calculations, the swarm is divided into two sub-swarms/sub-groups, each with its own temporary leaders. Once the obstacles have been bypassed, the sub-swarms merge back to reform the original swarm configuration optimally. However, if more obstacles are encountered after bypassing the first set of obstacles, the leaders in the sub-swarms perform the same calculations for their groups of agents as the main leader did for the whole swarm in the beginning. In other words, the operation continues recursively. The discussions and results obtained by testing the proposed approach are presented in Paper X.

1.3 Organization of the Thesis

The rest of the thesis is structured as follows. In Chapter 2, the basic concepts of Collision Avoidance Approaches and Multi-Robot Systems are covered. The developed obstacle detection and collision avoidance algorithm, tested on a mobile robot with ultrasonic sensor and bio-inspired camera, is presented in Chapter 3. Chapter 4, presents the developed formation morphing techniques for a swarm. A novel methodology of navigation based on translational coordinates is presented in Chapter 5. In Chapter 6, The novel methodology of energy-efficient navigation of the swarm through obstacles by minimizing the congestion is presented in Chapter 6. Concluding remarks and discussion is covered in Chapter 7. Finally, Chapter 8 provides the overview of the original publications.

2 Preliminaries

2.1 Collision Avoidance

For UVs to function either autonomously or semi-autonomously, a collision avoidance system plays a vital role. Collision avoidance is responsible for safe navigation of the UV, by either alerting the remote operator of the vehicle about the potential collision or taking control over the UV and diverting it in a manner to avoid colliding with the objects that pose a potential threat of collisions. A collision avoidance system contains perception sensors for observing the surroundings and detecting the objects in the vicinity and reacts based on the perceived information.

2.1.1 Obstacle Detection

For any collision avoidance system, detection of the obstacles in the proximity, i.e., perception, is the initial step. For monitoring the events in the environment, any autonomous agent needs to be able to detect its surroundings. Observing the neighborhood can be based on either active or passive sensors. Active sensors are the ones that have their own source, i.e., a transmitter, and a receiver, whereas passive sensors only have a receiver and no transmitter[1]. Active sensors emit a signal and read the reflected signal in order to detect the presence of any objects or obstacles in the vicinity. On the other hand, as passive sensors do not have their own transmitter for emission of radiation or signals, they rely on the signal or radiation discharged by the objects in the surrounding [12; 13]. A more detailed discussion on active and passive sensors and attributes of some common such sensors is given in Paper I.

An object is said to be detected when the distance d between the object and the agent is less than the detection range D_R and within the field of view (FoV) of the onboard sensor system, as shown in Figure 2.

This can be mathematically expressed as:

$$(d < D_R)\ AND\ (\theta_{obj} < FoV) \tag{1}$$

and

$$d = |r_A - r_{Obj}| \tag{2}$$

[1] https://internetofthingsagenda.techtarget.com/definition/active-sensor

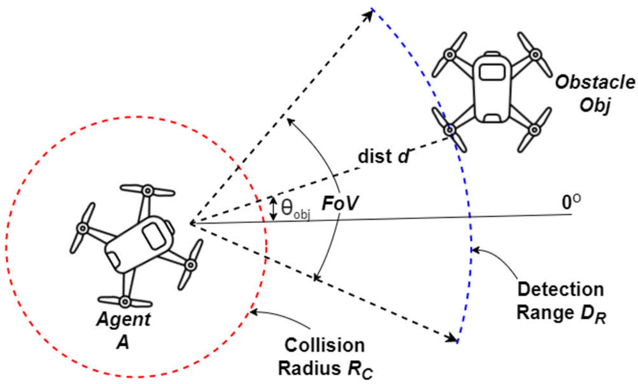


Figure 2. Collision Radius and Detection range

where r_A, r_{Obj}, D_R, θ_{obj} and FoV represent the position vectors of the agent and obstacle, detection range, the angle at which the object is detected, and field of view of the onboard sensor system, respectively. Furthermore, a collision is said to have taken place if the following condition is true:

$$d < R_c \tag{3}$$

where d is the distance between the agent and the obstacle and R_c is the collision radius.

2.2 Collision Avoidance Approaches

Collision avoidance approaches can be divided coarsely into reactive methods and deliberative planning based methods, Figure 3. Reactive planning refers to the model in which the agent perceives the information from the environment utilizing its local onboard sensors, detects objects in the vicinity posing potential collision threat, and react based on the information accordingly. On the other hand, in deliberative planning, the agent updates the map based on the information gathered by perceiving the surroundings. Afterward, it calculates the optimal collision free trajectory by keeping the initial goal under consideration. In order to be able to find optimal routes, the environmental map needs to be accurate. This has an adverse effect on the computational complexity, i.e., to perform all the required combinations, more processing power is needed. Therefore, especially in dynamic environments and when the system's computational resources are heavily constrained, this approach is not the most optimal and efficient solution (might not even be feasible) as the variables change over time, requiring frequent updating of the map, resulting in more computations and thereby in higher power consumption and/or potential violation of the real-time requirements.

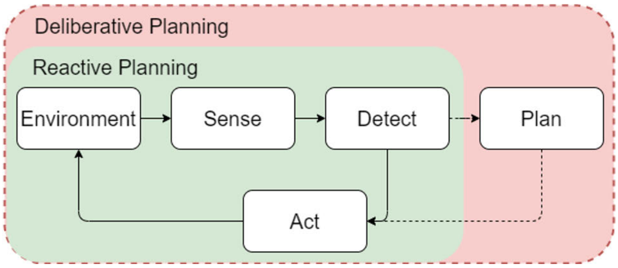


Figure 3. Reactive and Deliberative Collision Avoidance

Different collision avoidance methodologies can be categorized into the following methods: 1) *sense and avoid based*, 2) *force-field based*, 3) *geometric based*, and 4) *optimization based*.

1. *Sense and Avoid:* such approaches/methods work on the principle of see/sense the environment, detect any objects present, identify the objects that can lead to a potential collision if the same trajectory is followed, and react in order to safely maneuver the UV around the obstacles [14; 15].
2. *Force-field:* also known as vector-force field or potential-field based methods, such methods work on the principle of attractive or repulsive forces applied to the objects in the scenery for deviating from the path to avoid collisions [16; 17].
3. *Geometric:* such approaches derive an obstacle free path for the robot or UV by utilizing the information available based on the geometric constraints between the UV and the obstacle(s) [18; 19].
4. *Optimization:* these methods rely on the available geographical information in order to calculate an optimal route for the UV to navigate upon [20; 21].

Detailed descriptions, discussions, environmental effects, and the performance comparison w.r.t. several constraints between the approaches is given in Paper I.

2.3 Multi-Robot Systems: Swarm Robotics

In MRS, often referred to as multi-agent systems (MAS) as well, there are multiple robots, or agents, that are autonomous and capable of performing several tasks collaboratively and are able to take situation dependent decisions autonomously. Due to their ability to act autonomously, interact and collaborate with other neighboring agents, these agents can perform numerous autonomous actions to achieve their desired tasks [22]. In [23], Zakiev et al. draw a distinct line to differentiate from using the MAS and MRS interchangeably, as MAS is a broad terminology and is not specifically for robotics. However, in terms of robotics, MAS is used in cases where ideal models of the agents or robots are used for the analysis of the system.

Swarm robotics is the study of how multiple robots interact and coordinate with each other as well as the environment to fulfill the desired task or are able to imitate a certain behavior as a result of those interactions. The general rules that apply to swarms can be generalized as the robots act autonomously, are able to sense and react based on what they perceive in the environment they are situated in and are able to coordinate with other robots/agents in the swarm to be able to generate a behavior suitable to handle the dynamicity of the environment or the situation at hand [24; 25]. Taking inspiration from the swarming behavior of animals, such as wolf packs, birds, ants, and fish, researchers are focused on the development of different aspects of swarming to make them agile, robust, autonomous, scalable, and able to tackle unforeseen scenarios [24]. The underlying attributes for swarm robotics are mutually specified by various researchers as: the scalability ability of the swarm appropriate for any number of agents; relatively simple members; local sensing and local communications only ensuring flexibility and robustness of the swarm; homogeneity, i.e., the agents in the swarm should be similar to each other in order for it to be robust and redundant to overcome the loss of an agent easily; and all agents to be autonomous [26; 27; 28]. Some researchers add another attribute, awareness of other agents in the MRS, to the above-mentioned properties of the swarm [29]. However, it is not necessary for the agents to be aware of other agents within the swarm. Indeed, the agents may still be able to navigate and execute their tasks without having awareness of other agents'/robots' presence in the MRS by simply reacting to the other agents as the obstacles present in the environment [30]. A thorough examination of different factors involved in the control of a swarm and the aforementioned aspects in swarm robotics is presented by Chung et al. in [31] and Camazine et al. in [32]. Further analysis and the detailed relationship between the multi-agent systems, multi-robot systems, swarm robotics, sensor networks, and other multi-robot systems are presented in [23].

2.3.1 Design of Agents

Agents in robotics and the development to make them more agile, robust, and energy-efficient has been studied for a couple of decades. Agents can be software-based or hardware-based agents, and the combination of software agent and hardware is utilized to get past the challenges of trajectory planning and the coordination and cooperation between the agents [33; 34]. The design of agents can be based on the following classifications [34; 35; 36]:

- Reactive: such agents react to any changes in the environment or their surroundings or to a signal from another agent.
- Cognitive: such agents, by utilizing their designed intellectual architecture, can predict certain events and take decisions accordingly.
- Evolutionary: such agents function based on the elementary operations of evolutionary algorithms, such as mutate, reproduce, recombine, and select.

- Flocking: such agents mimic or replicate the behavior of the underlying entity, such as flocks of birds, to produce similar behavior of navigating together.

2.4 Formation Methodologies

The agents in the swarm are desired to maintain a certain formation shape in order to perform a certain task or while navigating towards their destination/goal. Formation maintenance methodologies or algorithms are responsible for defining the coordinates of every agent w.r.t. other agents within the swarm to maintain a certain defined shape [37; 38]. Formation maintenance can be broken down into the following jobs/tasks: maneuvering or directing the swarm from a source point to a goal or destination point, maintenance of the desired formation shape throughout the mission (keeping a certain shape or morphing the formation into another shape depending on the situation), reformation phase, i.e., directing the agents in the swarm to come back into the initial intended formation shape, and guiding the agents away from other agents within the swarm as well as from the objects in the environment to avoid potential collisions [39].

Table 1. Pros and Cons of Formation methodologies

Methodology	Pros	Cons/Limitations
Leader-follower based approach	• Ease of analysis • Flexibility, Easily scalable	• Leader dependent approach • Leader may not rely on follower's feedback
Virtual structure based approach	• Rigidly maintains the formation • Coordinate between the agents	• Cannot handle formation morphing • Computationally heavy • Will not be able to perform in congested environments due to limited capacity of dealing with collision avoidance, given the rigid body structure
Behavior based approach	• Multi-task missions • A single control command can be utilized to satisfy different assignments	• System stability cannot be ensured • Rather difficult to articulate the behavior of the overall system in mathematical terms • Not suitable for large scale deployments

Different methodologies to make the agents maintain the defined or desirable formation shape during the mission can be grouped into the following three approaches:

1. Leader-follower based approach: in this approach, every agent/robot functions

autonomously and individually. One agent is dedicated as the leader of the whole swarm. Other agents in the swarm, regarded as the followers, act accordingly to keep and maintain their respective positions relative to the leader in order for the formation shape to be maintained. Different variations in the design of the leader-follower based approach do exist to make it more redundant. For example, a virtual leader can be allocated [40]; a global/dedicated leader is assigned with several temporary leaders, and, as a fail-safety mechanism, in case the communication to the global leader fails, one of the followers takes charge as the temporary leader [39].

2. Virtual structure based approach: in this approach, the agents try to maintain a rigid geometric shape with respect to each other. In other words, the whole structure or the swarm is considered as a single agent or a rigid body and it is navigated accordingly as well [41]. Such approaches work on the principle of minimizing the error between the actual formation shape and the defined virtual structure [7].
3. Behavior based approach: in this approach, the agent's behavior is based on one of several pre-established strategies, such as coherence or collision avoidance [42; 43]. A hybrid vector weighted control function is responsible for generating the control commands to tackle with issues relating to the maintenance of the desired formation.

A summarized comparison between the aforementioned approaches is provided in Table 1. A comprehensive and comparative survey on the formation methodologies and system architecture of swarm formation is provided by Liu et al. in [5] and Oh et al. in [1].

3 Single Agent Collision Avoidance

For unmanned vehicles (UAV, UGV, USV) to be autonomous, the deployment of a state-of-the-art collision avoidance system is of utmost necessity. For situational awareness, unmanned vehicles, i.e., agents, are generally equipped with various ranging sensors and the ability to make appropriate/intelligent decisions depending on the task at hand. These agents can have different levels of autonomy, ranging from remote pilot control to partial autonomy to complete and independent autonomy. In principle, the collision avoidance systems work in a similar fashion with the main goal to allow the autonomous agent to navigate through an uncertain terrain while avoiding any potential collisions along the way. For developing an efficient and fault-tolerant collision avoidance algorithm, we opt for sense and avoid based approach due to its robustness, low complexity, and short response times. The developed collision avoidance algorithm is then tested for detection and avoidance in Paper IV and II. For collision avoidance, different sensors are needed among which some of them are used in this thesis, namely ultrasonic sensor and bio-inspired/event-based camera for testing the developed collision avoidance algorithm in real-time.

3.1 Ultrasonic Based Detection and Avoidance

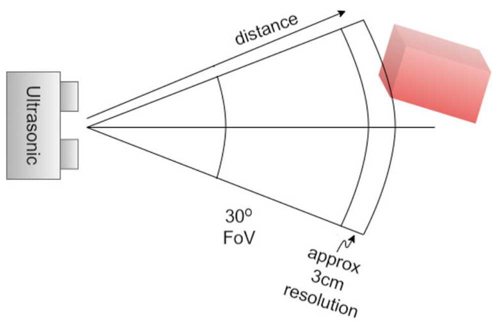


Figure 4. Field of view and resolution of ultrasonic sensors

Ultrasonic (US) sensors have a short range, are less expensive, and function independently of the lighting conditions. In this section, ranging sensor based obstacle detection and collision avoidance is proposed specifically with utilizing a single US sensor for detection, triangulation, and avoidance purposes. A speed controller is also designed for the UGV to be controlled while approaching the obstacle for smooth maneuvers. The work presented in Paper II, uses a single US sensor for detection, approximating the shape of the encountered obstacle, and bypassing the obstacle. US sensor has an FoV of 30°. Any obstacle that comes within that FoV is automatically detected, as shown in Figure 4.

In order to ascertain the exact points and angles of the obstacle in front of the sensor, some methodologies utilize multiple US sensors to triangulate and identify. However, in this work, we utilized a single US sensor equipped with a motor. As soon as an obstacle is detected, the sensor is rotated while approaching the obstacle to determine the location of the obstacle and subsequently bypass it. Moreover, a fault-tolerant methodology designed in the algorithm takes care of the occasional error in the sensor's reading, discussed in detail in the paper.

3.2 Bio Inspired Camera Based Detection

Another different approach is taken to test and cover the passive sensors based collision avoidance methodologies, such as traditional cameras. There is a significant amount of research being done to develop a state-of-the-art camera based collision avoidance system. However, due to certain limitations of every sensor, traditional cameras' limitations also affect their operability in many different situations, poor lighting conditions being one of the major ones. In Paper IV, we utilized a bio-inspired camera (event-based camera) for developing and testing our developed collision avoidance algorithm. Every pixel in the event-based cameras functions independently and photoreceptors of the pixels work on a logarithmic scale, making these cameras independent of the lighting conditions, i.e, able to capture the information daytime to night time. Furthermore, the high temporal resolution, low power, high dynamic range, and low latency of event cameras make them more suitable than traditional cameras. In this work, we developed an asynchronous adaptive collision avoidance methodology for the detection of obstacles and estimating their apparent velocities. For multiple detected obstacles, priorities are assigned by the designed algorithm based on their calculated point of impact with the agent. Based on these multi-priority obstacle avoidance switching is achieved.

4 Formation Morphing

The main goal in formation maintenance and morphing is to perform the operations while minimizing the overall energy consumption of the agents due to movement, i.e., minimal deviations from the desired trajectories. This becomes more challenging when the formation control is integrated with the collision avoidance system. Optimization of the resources to be utilized in the navigation of a swarm of autonomous agents is gaining traction in the research community. The main factor behind this surge amongst the researchers is due to the fact that the multi-objective approach, i.e., achieving different system goals in a near-optimal manner while keeping the system or design limitations (flight time, payload, etc) under consideration, is absent in the traditional operation of multi-agent systems [44]. While dealing with swarms of autonomous agents/drones and their navigation, the main issues that require to be systematically handled are maintaining the formation and collision avoidance amongst the agents themselves and the agents and the objects in the environment. While formation deals with the positioning of each agent in the swarm, collision avoidance is responsible for keeping the agents from colliding with other objects and the agents within the swarm. The main grounding of this chapter is the absence of a hybrid approach, i.e., formation maintenance, collision avoidance, variable speeds of the agents, and detection and handling of multiple obstacles in the collision zone, in the available literature.

4.1 Formation Maintenance and Collision Avoidance in a Swarm

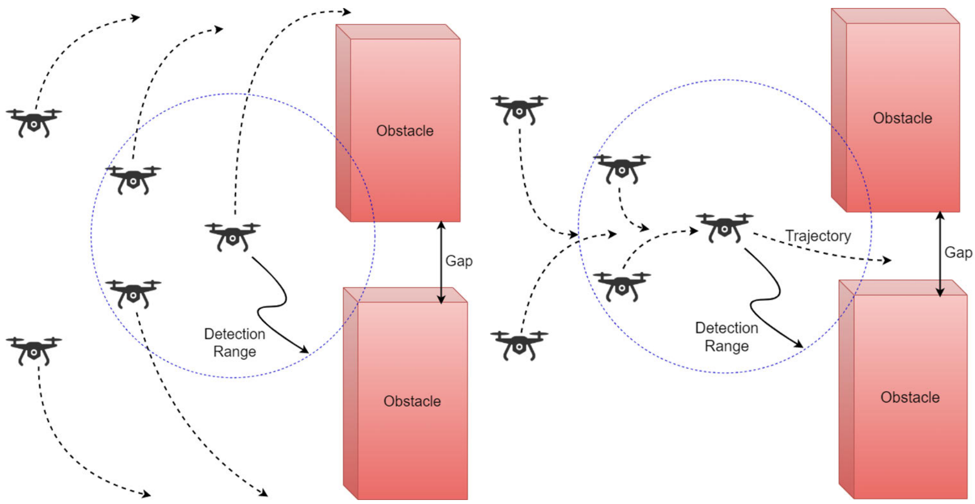
Formation maintenance and collision avoidance in a swarm are discussed in more detail in Paper III. In formation maintenance, the main emphasis is how to keep the agents in the swarm in the desired formation shape as optimally as possible. Similarly, in collision avoidance, the safe navigation of the agents is guaranteed. The main challenge arises, while keeping the formation and collision avoidance, when in the local sense and avoid scenarios, where the agents do not get any input about the movements from any central servers, and furthermore, the prior map knowledge is not available. Therefore, to keep a formation we need to consider the potential collisions, and similarly, for collision avoidance to function properly, the intended formation needs to be considered. Keeping this as the foundation, the work presented in Paper III, takes account of systematic integration of dynamic formation control together with the collision avoidance methodology for tight formation settings with agents' ability to accelerate or decelerate depending on the situation at hand. For the integration of these features and the whole process to be autonomous, the design approach is able to tackle with several abrupt or unanticipated factors into account, such as unknown/sudden appearance of the obstacles in the path, or available narrow opening between multiple obstacles, by prioritizing collision avoidance and formation control whenever deemed necessary.

It is shown, by comparison, that the approach is more efficient in maintaining tight formation, by accelerating/decelerating the agents based on the situation at hand, and distances between the agents even when obstacles are encountered or the agents are navigating through the gaps available between the obstacles. To see the efficiency of the work presented in the paper, it is also compared with a state-of-the-art work from J. Seo et al. [45].

4.2 Dynamic Formation Reshaping Based on Point Set Registration in a Swarm

The first phase towards the efficient formation maintenance and collision avoidance co-awareness scheme is discussed in Paper III. This work opened several further questions and highlighted several deficiencies in the existing methodologies that need to be addressed. One of them is the ability to reshape the formation of the swarm dynamically and efficiently, for instance in order to avoid collisions, or be able to navigate through an available gap between the obstacles, as shown in Figure 5.

Since in mobile agents, such as drones, limited battery capacity is one of the major concerns and therefore the focal point for derivations of efficient navigational algorithms along with the research for the development of better capacity batteries, energy-efficient communication between the agents and etc. For situations with no prior knowledge of the map, if the system is not able to detect multiple obstacles and find the available gap between them, the agents will deviate more from their paths, which effectively will result in shortened mission life, as shown in Figure 5(a). As shown the agents will utilize the onboard sensing system to detect any obstacles in the vicinity and act accordingly based on local information available. Subsequently, for reshaping purposes, if the agents slow down, excessively, to reshape and then continue navigation will also result in more time spent in the mission and will result in shortened mission life. The work presented in Paper V, presents an approach where based on the input from the collision avoidance system the formation control, utilizing the leader-follower based maintenance approach, dynamically reshapes the formation by temporarily reassigning the leaders for agents to follow to form a flexible queue shaped formation. After evading/going through the space between the obstacles, formation control enforces the point-set registration (PSR) [46; 47] to



((a)) Without Gap detection and dynamic reshaping

((b)) Dynamic Reshaping with multi-obstacle handling

Figure 5. Illustration of the approach with and without the dynamic reshaping of agents (a) illustrates the approach that does not calculate the available gaps with multiple obstacles and trajectories agents will take in order to bypass the obstacles, (b) illustrates the approach that detects the available gap between the obstacles and dynamic reshaping of the agents to go through that available gap

evaluate the optimal positions for the agents to navigate to. Based on the output from the PSR technique, the agents immediately start navigating towards the desired initial coordinates for maintaining the initial formation shape while navigating towards the goal. The proposed DFRPSR approach is compared with the local sense and avoid methodology to evaluate the efficiency of the proposed approach. Results and detailed discussions are presented in Paper V.

4.3 Energy efficient Formation Morphing for Collision Avoidance in a Swarm

After the first attempts in developing an energy-efficient, local sense and avoid based, solution for collision avoidance and formation maintenance in Papers III and V, the integration of these approaches leads to a comprehensive energy-efficient solution (EFMCA), which is discussed in more detail Paper VI. When a swarm deviates to avoid collisions with obstacle(s), this distorts the intended formation shape. After successful avoidance, the agents navigate back towards the coordinates in order to maintain the intended formation shape. This whole process of maintaining the shape, the deviation for avoidance, and reshaping must be fast, energy efficient, and reliable, i.e., safe. The proposed EFMCA approach, works on no-prior map information based navigational strategy, employs leader-follower based formation control, and sense and avoid based collision avoidance methodology.

The swarm upon encountering obstacle(s), goes into the deviation phase, which employs reflexive decision making due to the unreliability of the obstacle in the vicinity, with the main goal of minimizing the spatial deviation while maintaining the defined minimum safe distance. After avoidance is successful, to bring the agents back into the intended formation shape, i.e., the turn-back phase, an energy function is exerted for the swarm that is inspired by the energy function of TPS [48]. This energy function based turn-back phase minimizes the energy function in order to ascertain the navigational decision of each agent for resuming to the formation coordinates. The function given in the following equation is utilized for minimizing the energy function (E_{TPS}):

$$E_{TPS}(f) = \sum_{i=1}^{n} ||x_i - f(v_i)||^2 + \\ \lambda \iint [(\frac{\partial^2 f}{\partial x^2})^2 + 2(\frac{\partial^2 f}{\partial x \partial y})^2 + (\frac{\partial^2 f}{\partial y^2})] dxdy \tag{4}$$

In Eq. 4, λ denotes the scaling factor, x_i and v_i represents the locations of a point in the scene and the model respectively, and $f(v_i)$ represents the mapping function. Since, the efficient manner is to map the points, i.e., while in the disturbance phase, optimally and in an energy-efficient manner over the intended formation shape, therefore we set λ to zero and hence only the closest points are mapped without keeping the shape under consideration leaves us with the following equation:

$$E_{TPS}(f) = \sum_{i=1}^{n} ||x_i - f(v_i)||^2 \tag{5}$$

The mapping process is performed, by minimizing the temperature function in Eq. 5, from maximum disturbance to the intended formation shape. Once this is calculated the agents start navigating, following the shortest path, towards the calculated hypothetical coordinates to reach its position, illustrated in Figure 6.

The presented work proposed the following new concepts w.r.t. the state-of-the-art:

1. A new idea where the random dispersion of agents is initiated for reducing the time and energy upon detection of an obstacle in the initial phase
2. During the second phase of obstacle detection, a new concept of reducing the time and energy by utilizing the TPS algorithm is proposed
3. comprehensive simulation results are also provided along with the comparison of the proposed scheme with existing state-of-the-art to highlight the efficiency of our technique

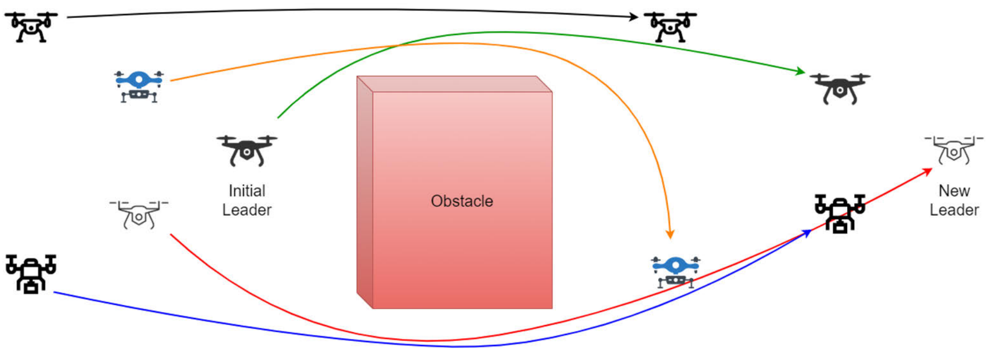
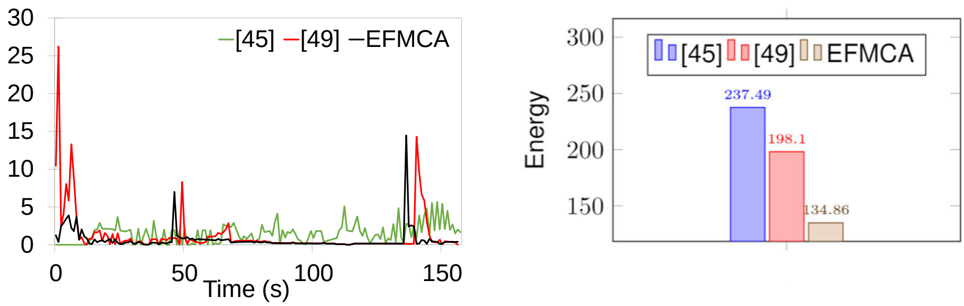


Figure 6. Illustration of formation morphing and collision avoidance



((a)) Change in Temperature of the system as a whole **((b))** Total Energy of the system

Figure 7. Comparative results of other known techniques [45] and [49] with EFMCA [39]

Figure 7 shows the important results obtained. The results shown in Figure 7(a) show the sum of all the disturbances during the course of the mission by all the agents of the swarm. The bar graph shown in Figure 7(b), shows the energy of the system for three schemes compared together, where it is evident that utilizing the EFMCA approach, the swarm suffers considerably less disturbance in comparison with other known schemes. Detailed analysis is provided in Paper VI.

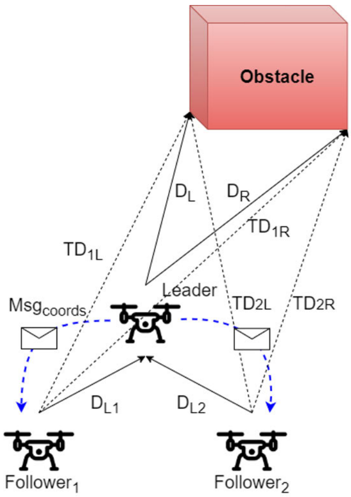
5 Translational Movements

In the previous chapter, it was shown how to minimize the energy consumption of the swarm based on the movements of the agents and a new technique was proposed to make the system energy efficient by countering the disturbances caused by the presence of obstacles in the vicinity of the swarm. In this chapter, we look at energy efficiency from a different perspective, as movement related consumption can only be minimized to a certain extent. Here we analyze the energy consumption due to the use of ranging sensors, such as LiDARs, sonars, traditional cameras, and so on. Being able to perceive the environment/surroundings works as the foundation and fundamental part for an agent to be able to autonomously navigate in any environment. Perception, i.e., the eyes of the agent, is performed by utilizing the variety of ranging sensors (or their combinations) available to scan the surroundings and detect any obstacles in the vicinity that can lead to potential collisions. All different types of such ranging sensors can be enveloped into either active or passive sensors. Active sensors, such as LiDAR, sonar, and Radar, have their own source/transmitter that emits a signal, this signal when bounces off an object is then read by the receiver of the sensor. However, as passive sensors, such as cameras and IR, do not have their own source, they rely on the energy discharged by the objects, i.e., the scene under observation. A detailed discussion about the fundamental functioning of active and passive sensors and different common sensors utilized for perceiving the environment is given in Paper I.

In the existing literature, most of the research is focused on making the system efficient by optimizing recharging [50], route planning [51], or external influences, such as wind direction [52; 53]. After presenting the EFMCA algorithm, in Paper VII, we present a new method of reducing the battery consumption due to sensors usage in a swarm of autonomous agents by using translational coordinates.

5.1 Translational Coordinates based Navigation of a Swarm

The work presented by Paper VII presents a new idea of reducing the energy consumption of the follower agents in a swarm by turning the ranging sensors off. The swarm utilizes a leader-follower based approach for keeping the formation, due to its reliability, ease of implementation, and scalability. For collision avoidance, the sense and avoid based approach is utilized. Whereas, the agents are modeled as reactive



((a)) Translational coordinates calculation

Variable	Description
D_L, D_R	Distance to obstacle's left and right end from leader
D_{L1}, D_{L2}	Distance between follower 1 and the leader and distance between follower 2 and the leader respectively
TD_{1L}, TD_{1R}	Translated distance to obstacle's left right end from follower 1
TD_{2L}, TD_{2R}	Translated distance to obstacle's left right end from follower 2
Msg_{coords}	self and obstacle's coordinates transmitted by leader to its followers

((b)) Explanation of the variables in Figure 8(a)

Figure 8. Illustration of translational coordinates calculation

agents, as they react to any changes in the environment or upon receiving a signal from another agent in the swarm. The main concept behind the approach presented in this paper is that all the agents in the swarm besides the leader turn off the ranging sensors when the environment is static. The leader keeps sensing the environment. As soon as there is any obstacle detected by the leader, it sends a signal to its followers, indicating the presence of a potential threat forcing them to turn on their sensors. For navigational purposes, the leader constantly transmits its coordinates to the followers along with that of the detected obstacles (if any). Follower agents then translate the coordinates according to their own positions, as shown in Figure 8. Figure 8(a) illustrates the calculation process and the description of the variables used are given in Table in Figure 8(b). Followers turn on their sensors if the detected obstacle is in their path and continuing the same trajectory can lead to a collision. Furthermore, as a fail-safe, if the communication with the leader is lost, i.e., the follower agent has not received a signal from the leader for a certain period of time, it declares itself as its leader and switches itself to active mode by turning its sensors on.

In the experiments performed, it is shown that the consumption due to sensors usage can be reduced by a substantial amount of about 50%. Such an approach can be very helpful for increasing the mission life on a single charge when there are no dynamic variables in the environment.

5.2 Autonomous Swarm with Adaptive Conscious Agents

After the successful verification of the approach described in Paper VII, the extended approach is developed in Paper VIII. In this work, the energy consumption due to sensor(s) usage is minimized even further by injecting the adaptive consciousness into the agents in the swarm. This is achieved by relying on the information that an agent receives from its neighbors for navigational purposes and after performing necessary calculations, the agent itself is able to comprehend the situation around it and thereby decide on its own if it is necessary to switch to active mode, as illustrated in Figure 9.

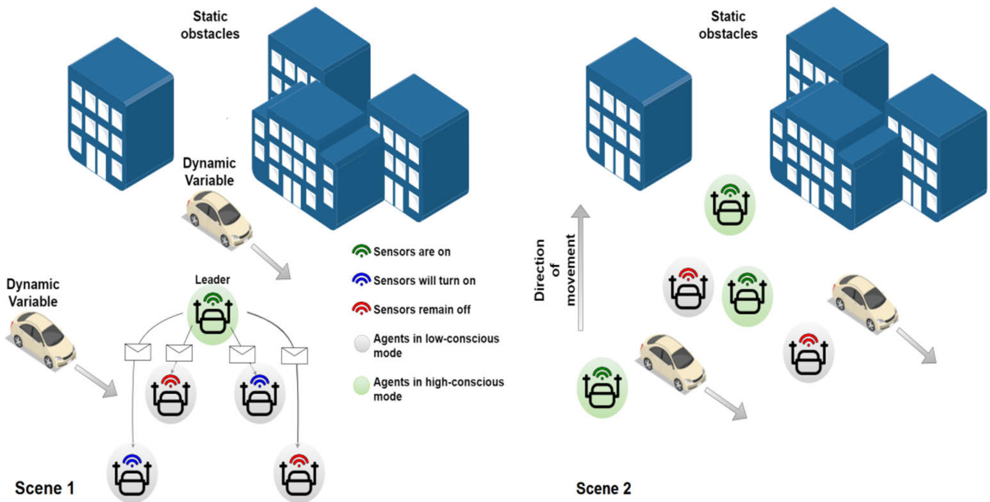


Figure 9. Illustration of adaptive conscious agents utilizing translational coordinates

The leader, upon detection of obstacle(s), sends its location along with the coordinates of the detected obstacles (if any). The followers perform the necessary calculations and translate the coordinates relative to their respective positions. Upon performing the calculations, the follower agent decides itself whether progressing on the same path is safe or is it supposed to divert in case an obstacle is in the current trajectory. Furthermore, in case of a moving obstacle, by translating the information received and comparing these translated coordinates with previous readings, the follower agent can realize itself without turning on its ranging sensors, whether the obstacle is stationary or moving. In addition, based on the mathematical calculations, the agent can also identify the apparent velocity of the dynamic obstacle and the direction in which it is traveling. Based on this information if deemed necessary, i.e., a potential collision threat if navigating on the same trajectory, the follower agent can decide for itself when to turn on its ranging sensors to perform collision avoidance. The results for detailed investigation are presented and discussed in Paper VIII.

6 Congestion Awareness

The previous chapter highlighted the aspects of reducing the energy consumption of individual agents and therefore reducing the overall energy consumption of a swarm. Until now in this thesis, we have discussed how to efficiently manage the organizational structure in a swarm by reducing the disturbances in the formation caused due to the presence of obstacle(s) and how to further reduce the energy consumption of the swarm by adaptively switching the ranging sensors on and off of the individual agents depending on the situation at hand. In this chapter, a new aspect of reducing the energy consumption of the swarm is discussed. The technique may not necessarily reduce the consumption of individual agents, in fact, may result in higher consumption of some individual agents, but reducing the consumption when taking the whole swarm into account. When operating in unknown environments, with no prior map information and local sense and avoid capability, the agents in the swarm act with what they observe while utilizing their onboard sensors. In order to be able to find optimal routes, the individual agents choose the shortest path for avoiding the encountered obstacle. This is the apparent best solution for the agents in the swarm, however, it may have an adverse effect on the overall efficiency of the swarm. The existing literature mostly focuses on prior map information for drawing efficient trajectories for the agents to navigate without causing delays. Moreover, any change in the environment can lead to re-calculation of those optimal trajectories, as the change may not be the optimal solution anymore. When a swarm, with no prior map information and utilizing only onboard sensors to observe its surroundings, navigating towards its destination encounters obstacles in its path, it needs to have an efficient mechanism to bypass the obstacles. While utilizing leader-follower based formation control, upon encountering the obstacles, the agents in the swarm may only follow their respective leaders and thence the same trajectory for avoiding the obstacles in their path [54]. Or they may utilize the comprehensive observe, decide, and act methodology to break away from the formation to choose the best path based on their own respective coordinates [55]. However, when the majority of the agents have the same shortest path for bypassing an obstacle, they will have to reform while decelerating significantly, to allow other agents to navigate, resulting in time delays, leading to the higher energy consumption of the individual agents as well as the swarm.

6.1 Centroid Based Formation Maintenance and Collision avoidance

Leader-follower based approaches have one major drawback, i.e., the dedicated leader. In case the leader is lost or the communication fails, the rest of the swarm will not be able to function properly, as the agents in the swarm are dependent on the leader. Moreover, while navigating in a leader-follower formation, an efficient approach needs to be in place for the agents to break away from the formation to perform collision avoidance in an efficient manner. To tackle these issues, in work presented in Paper IX, we define the dynamic selection of the leader based on certain conditions. In order to find the best avoidance routes for the agents, the space is divided into a uniform sized grids/cells, where the grid size is determined based on the drone's size plus its safe zone as shown in Figure 10. Based on the occupancy of a cell, occupied or unoccupied, its state is changed between one and zero respectively.

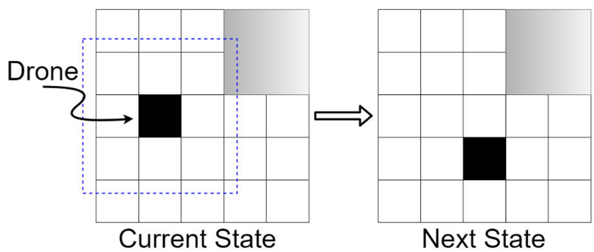


Figure 10. 2D model of a drone and an obstacle illustration the current and next state movement

For determining whether the detected obstacle is stationary or dynamic, we utilize the following equation:

$$v_o = \frac{\Delta d_{oi}}{\Delta t} \tag{6}$$

where v_o is the calculated velocity of the obstacle and Δd_{oi} is found by utilizing the following relation:

$$\Delta d_{oi} = d_{ti} - d_{ti-1} - d_{ui} \tag{7}$$

where d_{ti} is the distance between the obstacle and the agent (current reading), d_{t-i} is the distance between the obstacle and the agent at previous interval, and d_{ui} is the distance travelled by the agent as illustrated in Figure 11. Based on these calculations, the point of impact is calculated and the avoidance maneuver is initiated accordingly.

Upon successful avoidance, in the reformation process the centroid of the swarm, calculated as shown in Eq. 8, is stabilized to bring the drones/agents back to the desired locations in an optimal manner.

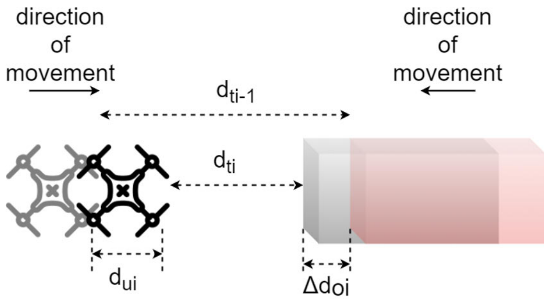


Figure 11. Illustration of moving obstacle detection and calculation

$$(\bar{x}, \bar{y}) = \left(\frac{1}{n} \sum_{i=0}^{n} x_i, \frac{1}{n} \sum_{i=0}^{n} y_i \right) \tag{8}$$

The agents are navigated back to the desired formation locations without keeping the restriction of neighboring nodes as same to make the whole process smoother and more efficient. The experimental results showed the efficiency of the proposed approach as compared to the unique leader based approach.

6.2 Congestion Aware Formation Morphing

The multi-objective formation morphing and collision avoidance methodologies discussed previously are being extended here by taking into account the over congestion delays that may happen due to overpopulating the available gaps between the obstacles. The abstract level system architecture for the approach proposed presented in Paper X is shown in Figure 12.

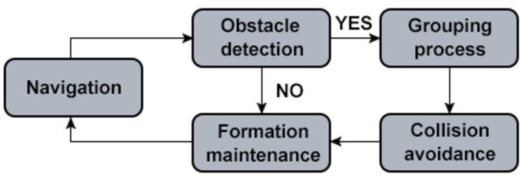
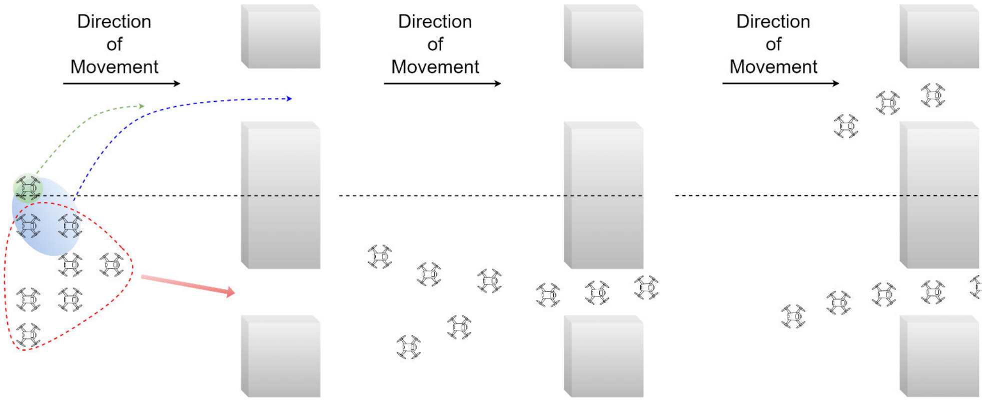


Figure 12. Block diagram for congestion-aware avoidance approach

Since the agents in the swarm are navigating without the prior knowledge of the whereabouts of the obstacles in the vicinity, if each agent chooses the trajectory that is optimal for itself, it may lead to a poor overall solution for the whole swarm as illustrated in Figure 13.

Figure 13(a) shows the moment the obstacles enter the detection range of the leading agent of the swarm. The drones encircled in a red dotted line will navigate



((a)) Initial setup **((b))** Illustration for leader-follower avoidance **((c))** Illustration for congestion aware avoidance

Figure 13. Swarm encountering set of obstacles (a) initial formation shape, drones encircled with red dotted line will navigate to same gap based on their respective shortest paths and the drone highlighted in green will navigate to its respective shortest path, (b) shows the leader-follower based swarm distribution while performing avoidance, (c) shows the congestion aware swarm distribution while performing avoidance

towards the same available gap between the obstacles based on their respective shortest path avoidance. Whereas, the drone highlighted in green, will navigate towards the other available gap between the obstacles based on its respective shortest path (green arrow). If the traditional approach of leader-follower based formation control approach is utilized, all the agents in the swarm will navigate towards the same available gap between the encountered obstacles as shown in Figure 13(b). The only difference between this and Figure 13(a) is that one drone whose shortest path is different than the rest of the swarm. Other than that, there will be delays due to congestion, as illustrated in Figure 13(a), leading to increased mission completion time and increased energy consumption of the drones as well as the whole swarm. However, while employing the proposed congestion aware approach, the delays due to overpopulation of either gap are minimized as illustrated in Figure 13(c).

The leader of the swarm, upon detection of the obstacles, evaluates the possible combination of group of drones for both gaps with the time it takes for the last drone in either group to pass the obstacles. Based on the estimated calculations, the leader instructs the drones (highlighted in blue for illustration purposes, in Figure 13(a)) to choose the path (shown by blue dotted line) in order to minimize the congestion. As it is visible that the drones instructed by the leader have to take a distance penalty, which is not optimal for those drones individually, however, it is the optimal solution for the swarm as a whole.

The grouping process, illustrated in Figure 14, is dependent on the number of obstacles encountered and the drones distributed in the groups is calculated based on

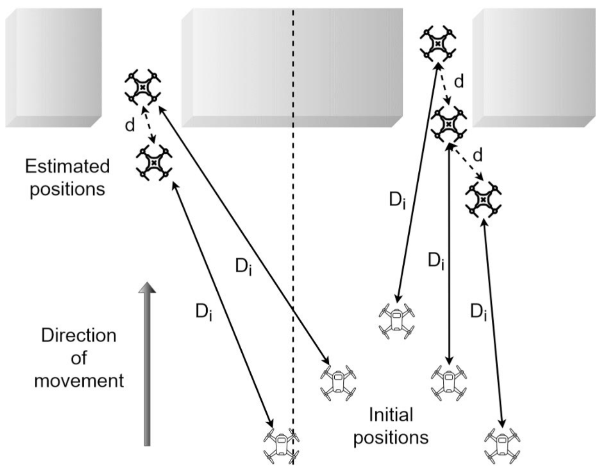


Figure 14. Grouping Estimation Process, here the initial V-shaped configuration is sketched along with the estimated positioning of the drones

the following metric:

$$\tau = \frac{\Sigma D_i}{v_{i \in J}} \tag{9}$$

where τ is the overall time, v_i is the velocity of the drones, J is the number of drones, and ΣD is the summation of the distance from each drone's current position to the calculated/estimated avoidance location. D_i is dependent on the average distance of the agents from each other in each group set and can be given as:

$$D_i = f(\overline{d}_{g \in G_i}) \tag{10}$$

where G_i is the group set, and $\overline{d}$ is the calculated average distance of the drones from each other.

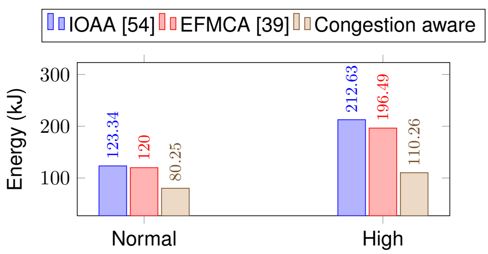


Figure 15. Total energy consumption of the swarm for all techniques in normal complexity and high complexity environmental scenarios

In the performed experiments, it is shown via comparative results (Figure 15) that the energy consumption can be reduced significantly by employing the proposed approach in comparison with the traditional methods. Implementation and algorithmic descriptions are provided in detail in Paper X.

7 Conclusions

The need for energy-efficient formation and collision avoidance methodologies for unmanned vehicles, UAVs or UGVs, is evident, particularly when navigating in unknown environments with no prior map information. This is due to the fact that these mobile robots have limited resources such as battery capacity. One of the challenges is to efficiently bring the agents back into formation after the formation is disturbed due to environmental factors, such as obstacle detection and avoidance. If the agents retain their initial positions in the reformation process, it may not be optimal in all cases, as some of the agents may need to wait for their respective leaders to retain their respective positions. In this dissertation, we analyzed the energy efficiency in formation morphing and collision avoidance of a swarm of robots and introduced multi-objective congestion aware morphing and collision avoidance and adaptive conscious agents utilizing translational coordinates approach to navigate. We first covered the agitation reduction while maintaining the formation and efficient reformation and presented a novel formation collision co-awareness approach. A closed-loop feedback system is used to minimize the agitation or disturbance in the formation shape that occurs due to the presence of the obstacle(s) in the vicinity. That is achieved by utilizing the TPS-inspired algorithm that generates the next points for the agents to navigate to. For collision avoidance, the algorithm breaks out of the feedback loop, and once the collision is avoided successfully, the system enters the feedback loop once again for an optimal reformation process. The developed scheme is compared with the recent state-of-the-art methodology to analyze the efficiency, and the obtained results show the effectiveness of the proposed scheme in providing energy-efficient outcomes. The main challenge in finding the optimal solution was to think outside the box and find an existing algorithm or methodology, from any field, that can assist in achieving the outcome or to design a completely new methodology, if existing methods are not applicable.

From another perspective, the energy consumption due to the use of ranging sensors for observing the surroundings by an agent is discussed in this thesis. We presented and introduced this unique technique, where the agents are able to turn off their ranging sensors depending on the environmental constraints and are able to navigate by only listening to the information received from their leader. The follower agents receive the coordinates of the obstacles, detected by the leader, as perceived by the leader. After receiving the information, the follower agents translate the coordinates according to their respective locations. Moreover, after translating the coordinates, the follower agents are also able to calculate if the detected obstacle is stationary or dynamic, and, in the case it is dynamic, the velocity of the obstacle. Based on these calculations, the agent can itself decide if it is necessary to turn on the ranging sensors to perform collision avoidance actively or if safe navigation is possible without doing so. The results obtained show the significant reduction in the energy consumption that can be achieved by utilizing this innovative technique.

Finally, another track of minimizing energy consumption is discussed in this dissertation, which covers the energy consumed by the agents due to unnecessary waiting time that is added due to slowing down or hovering because of congestion that happens when all or most of the agents navigate towards the same route, i.e., when more than one routes are available. When dealing with navigational energy consumption minimization, the existing approaches lack an approach that can help in minimizing the delays that may occur due to environmental constraints. The main challenge in tackling this issue was to be imaginative and think creatively in designing and ultimately proposing a completely new approach/methodology that fills in the existing gap. When a swarm is navigating in an unknown or unfamiliar environment, with no known information about the obstacles, it is imperative for the swarm to be able to dynamically and at run-time morph the formation while avoiding the obstacles in its path. This can lead to all or most of the agents in the swarm navigating towards the same side or gap that is available between the encountered obstacles. This issue of congestion or overpopulation is handled by the introduced congestion-aware formation morphing methodology. As soon as the obstacles are detected by the leading agent, it estimates the population factor of the agents in the sub-groups/sub-swarms, depending on the obstacles, and instructs the agents to a trajectory that results in minimal congestion and is optimal for the swarm as a whole. The efficiency of the approach is shown by a comparative analysis of the obtained results with the traditional approaches. It is shown that in the performed experiments, the energy consumption of the swarm is reduced significantly.

For future work, there are numerous ways in which the work discussed in this dissertation can be improved. There can be various directions in which the proposed strategy of reducing energy consumption due to the use of ranging sensors can be improved, for instance, the effect of power consumption due to wireless communication and the effect of processing the information and coordinates on the battery life can be analyzed. How much efficiency is affected if the agents in the swarm are close or far away from each other? Another possible improvement can focus on dynamic election-based swapping of the agents by monitoring the battery status of the agents. If the agents on the outer layer of the formation work in active mode, i.e., keeping their ranging sensors on, while the inner agents in the formation only use translational coordinates, how efficiently the swapping can be performed? Furthermore, the developed methodology of formation morphing with congestion-aware collision avoidance can be improved by including the computational times and furthermore the communication delays that can affect the outcomes. Another possible future direction for this work can be focused on 3-dimensional congestion-aware collision avoidance. How significantly the currently proposed methodology can be improved? Further improvements, not limited to the ones mentioned above, can facilitate the research community in improving the presented methodologies for the betterment of society. In such a manner, autonomous systems will become more robust, reliable, and trustworthy. From a different perspective, fault-tolerance and cyber-security are some of the other significant challenges that bring up trust issues, among others, especially when considering human-robot collaboration.

8 Overview of Original Publications

Summarized analysis of the published articles from this thesis is presented below.

8.1 Paper I: Unmanned Aerial Vehicles (UAVs): Collision Avoidance Systems and Approaches

In this paper, a comprehensive and exhaustive literature survey is performed, that lays the foundation of the methodologies developed and presented in this dissertation. The survey covers collision avoidance systems and approaches with the main emphasis on unmanned aerial vehicles. The major modules that a collision avoidance system is dependent on are laid down, starting from perception to collision avoidance approaches. Perception is dependent on different types of ranging sensors, and they can be generalized into either active or passive sensors. A detailed discussion on such sensors is presented with the focus on their technical functionality and how they are utilized in state-of-the-art systems. In addition, the collision avoidance approaches are categorized into four major categories: 1) sense and avoid, 2) force field, 3) geometric, and 4) optimization based methods. An in-depth analysis is presented with the support of recent research advances in the field. Finally, performance analysis is presented based on the comprehensive review performed.

Author's contribution: The author contributed by performing an exhaustive literature review, compiling the literature, and tabulating the characteristics of the approaches for comparison. The author also contributed to the write-up and presentation.

8.2 Paper III: Formation Maintenance and Collision Avoidance in a Swarm of Drones

In this paper, a multi-priority control strategy is proposed for formation and collision avoidance co-awareness with the aim of minimization of the response time and energy consumption. To achieve this, the feedback-based control loops of the proposed strategy monitor the relative positions of the agents, a boolean value by a local sensor, and the distance of the detected obstacle to the agent. The relative position of the neighboring agents is utilized in formation maintenance, detection of an obstacle by a local sensor is indicated by a boolean value which is utilized by formation maintenance as well as collision avoidance module, and the distance of the detected obstacle is utilized by the collision avoidance for high priority avoidance maneuvers in critical situations.

The primary contribution of this paper is as follows:

- Multi-priority control strategy for formation/collision co-awareness
- Multi obstacle aware collision avoidance methodology, for gap detection
- Fault tolerance handling by making a temporary formation in case of lost UAVs

Author's contribution: The author implemented the multi-priority control strategy and is responsible for the experimental setup, performed experiments, and the evaluation of the algorithm and the obtained results. The author also contributed to the write-up and presentation.

8.3 Paper V: Dynamic Formation Reshaping Based on Point Set Registration in a Swarm of Drones

In this paper, a dynamic formation reshaping technique is proposed that considers the desired formation shape, collision avoidance, and reformation in an optimal manner. The technique presents a set of routines for the reshaping phase of the formation from one shape to another dynamically. When the swarm approaches obstacles and there is a narrow gap between the obstacles that is safe enough for a drone to pass through, this technique dynamically reshapes the formation shape into a queue formation for optimal navigation of the swarm. while morphing the formation for collision avoidance, the agents select their temporary leaders and move to maintain the defined minimum distance between agents for tight queue formation. After the obstacles are bypassed, the agents in the swarm are brought back to the original intended formation shape with the help of point set registration. The results obtained show the effectiveness of the technique as compared to utilizing only local sense and avoid technique.

The key contribution of this paper is as follows:

- Dynamic transformation of formation shape into queue formation for collision avoidance
- Dynamic selection of temporary leaders by the agents

Author's contribution: The author proposed the idea of dynamic formation reshaping and implemented the algorithm to verify the results. The author also contributed to the write-up and presentation.

8.4 Paper VI: Energy-efficient Formation Morphing for Collision Avoidance in a Swarm of Drones

In this paper, we propose a novel energy-efficient formation morphing for collision avoidance approach. Due to the uncertainty of the obstacles, the proposed approach uses reflexive decision making in the deviation phase with the goal of minimizing the spatial deviation without violating the safe distance. For bringing the swarm back into the original formation shape, we propose a novel idea of utilizing the energy function inspired by the thin-plate spline technique. Reduction of the total energy of the system is achieved by systematic integration of these modules, i.e., collision avoidance, formation maintenance, and formation-collision co-awareness. The results obtained showcase the effectiveness of the approach, i.e., timely and aggressive reduction in the agitation in the formation shape caused by obstacles. We compared the results with state-of-the-art and reported the results, showcasing the efficiency of our proposed methodology.

The key contributions of this paper are as follows:

- Random scattering of the drones in the phase of obstacle detection, to reduce time and energy
- Reduction of time and energy by employing the thin-plate spline algorithm
- Non-rigid mapping for reducing the lag caused by avoidance maneuvers

Author's contribution: The author proposed a novel methodology, developed a simulation platform for implementation, and implemented and compared the algorithm with recent works to determine its efficiency. Furthermore, the author implemented the techniques in an open-source environment for validation of the obtained results. The author also contributed to the write-up and presentation.

8.5 Paper II: Ultrasonic based Object Detection and Collision Avoidance Method for Autonomous Robots

In this paper, the developed collision avoidance algorithm is deployed on a mobile robot for testing the efficiency of the algorithm. The mobile robot equipped with a single ultrasonic sensor navigated through the encountered obstacles safely. Furthermore, the algorithm was also able to detect the shapes of the encountered obstacle and decide to choose the shortest path based on the detected shapes.

Author's contribution: The author contributed by setting up the hardware, deploying the algorithm on the hardware, and performing experiments to verify the successful collision avoidance in the performed experiments. The author also contributed to the write-up and presentation.

8.6 Paper IV: Night Vision Obstacle Detection and Avoidance Based on Bio-Inspired Vision Sensors

In this paper, we proposed obstacle detection and collision avoidance while utilizing an event-based camera. Traditional cameras are dependent on the lighting conditions, and especially during the nighttime, it is very challenging for traditional cameras to capture the whole scenery and the changing events. Therefore, we utilize an event-based camera for performing object detection. Using the Hough transform technique, the proposed algorithm filters the background noise and extracts the object. Once the objects are extracted, their depth is determined by utilizing LC-Harris. Afterward, for effective avoidance, the proposed asynchronous adaptive collision avoidance (AACA) algorithm is employed.

The key contributions of this paper are as follows:

- Asynchronous adaptive collision avoidance algorithm

Author's contribution: The author contributed to the implementation of the proposed AACA algorithm. The author also contributed to the write-up and presentation.

8.7 Paper VII: Navigation of Autonomous Swarm of Drones using Translational Coordinates

In this work, we propose a novel translational coordinates based navigational scheme for a swarm, navigating in a static environment, to reduce the power consumption of individual agents of the swarm. When the environment is static, i.e., stationary obstacles, the agents in the swarm can navigate by simply listening to the leader and then translating the coordinates of the surroundings, as perceived by the leader, to their respective locations. We showed by simulations, that the swarm can maintain the formation while navigating and also able to avoid colliding with the obstacles by applying the pre-established formation scheme with feedback cross-referencing between the agents. Simulation results show that, by employing the proposed scheme, the consumption of the swarm can be reduced by 50% in the performed scenario.

The key contribution:

- Translational coordinates based navigation of a swarm in a static environment
- Adaptive autonomous mode for agents for smooth transitions between active and passive navigation
- Fault tolerance in case of leader loss or errors in the translation of coordinates

Author's contribution: The author contributed to proposing the idea of translational coordinates based navigational scheme, implementing, and evaluating the results obtained. The author also contributed to the write-up and presentation.

8.8 Paper VIII: Energy-efficient Navigation of an Autonomous Swarm with Adaptive Consciousness

In this work, we propose a novel navigation of a swarm by injecting adaptive consciousness in the agents for reducing energy consumption due to the use of ranging sensors. In a swarm, if only the leader or a set of specified agents take the intelligent decisions, while the rest of the swarm navigates by listening to the information transmitted by their leader(s), energy consumption can that is due to the usage of ranging sensors can be reduced significantly. While navigating, only the leader (or the specified set of agents) will keep their sensors turned on to observe the environment, whereas the rest of the agents in the swarm will navigate by only listening to the leader's transmitted information. In the case of dynamic obstacles, the agents can realize the velocities of the obstacles by analyzing the translated coordinates. Moreover, instead of methodically or periodically or being instructed to turn the sensors on, the agents themselves decide by analyzing the translated coordinates, if it is necessary to turn on the ranging sensors or not. In this manner, even further power consumption is reduced making the swarm as a whole energy efficient. The simulation results show the relation between power saving and the environmental dynamicity and the efficiency of the proposed scheme in comparison with previous and traditional methods. It should be noted here that the presented method can be further improved by extending the work and integrating advanced techniques in it.

A prior version of this technique has been proposed and discussed in Paper VII. This is an extended work with the key contributions as follows:

- Extending from stationary obstacles to dynamic obstacles handling as well
- Adaptive conscious agents, i.e., the agents can themselves decide when to turn on their ranging sensors to perform collision avoidance actively
- Utilizing the translated coordinates, the agents can determine the direction and the velocity with which the obstacle is moving

Author's contribution: The author contributed in proposing this approach, implementing it, gathering the results and analyzing them, and comparing the efficiency of the proposed scheme with traditional methods. The author also contributed to the write-up and presentation.

8.9 Paper IX: Cellular Formation Maintenance and Collision Avoidance Using Centroid-Based Point Set Registration in a Swarm of Drones

In this paper, we propose a methodology for low-energy collision avoidance and formation maintenance in a swarm of drones. In order to temporarily break the formation to perform efficient collision avoidance, a cellular automata inspired rules are defined utilizing which the optimal morphing is acquired while minimizing the energy and time. For the near-optimal reformation phase, the temperature function reduction approach from point set registration is utilized with the main objective of minimizing the disturbance or agitation in the formation while minimizing the overall settling time by stabilizing the centroid of the swarm. The ability of re-electing the leader of the swarm dynamically, makes the process smooth and reduces any delays that may occur in bringing the dedicated leader back to its position. In this manner, the time it takes to reach the destination is also minimized and therefore minimizing the overall energy consumption of the swarm as well.

The key contributions of this work are as follows:

- Centroid-based formation stabilization with non-rigid mapping of the agents
- Run-time calculation of danger zone, by calculating of point of impact based on information available locally

Author's contribution: The author implemented the scheme with different number of agents and presented the comparative results. The author also contributed to the write-up and presentation.

8.10 Paper X: Congestion-Aware Formation Morphing for Collision Avoidance

In this work, we propose a novel methodology for minimization of unnecessary delays due to congestion that may happen especially when a swarm utilizing only local sensors to observe the environment, navigates in unfamiliar territory with no prior knowledge of the map or obstacles in it. When a swarm comes across obstacles, the agents in the swarm, either utilize their respective minimal deviation path based avoidance maneuvers or follow their leader to bypass the obstacles. These can lead to overpopulation on either side of the obstacles. To address this issue, in our proposed congestion aware scheme, the leader access the situation at hand, i.e., the number of obstacles and openings between them accordingly. Upon evaluating the openings, that are safe for the agents to navigate through, the leader then performs an estimation based calculation to find out the best possible division of the agents, by testing different morphing combinations. Based on these calculations, the swarm is divided into sub-swarms/sub-groups, each with their own temporary leader, and the agents are instructed to follow the respective leader of the sub-group based on the defined metrics. For the convergence phase, i.e., reformation, the previously developed TPS inspired minimization of temperature function based turn-back methodology is exploited. The results obtained show significant improvement of around 50% lower energy consumption over the traditional methods. It is important to note here that the proposed technique can be further improved by integrating more advanced techniques in the current methodology.

The key contributions of the proposed work are as follows:

- Pre-assessment of the encountered obstacles for most optimal configuration of collision avoidance maneuvers

- Estimation technique for obtaining the optimal number of agents into subgroups
- Technique for determining which agents should take the distance penalty
- Congestion aware formation morphing technique

Author's contribution: The author proposed the congestion-aware methodology and implemented it along with the traditional methods for examination and comparison purposes. The author also contributed to writing and presenting the work.

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