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High Index Multi-Layer Metasurfaces for Broadband Polarization Control

Grbic, Anthony
REGENTS OF THE UNIVERSITY OF MICHIGAN
1109 GEDDES AVE, SUITE 3300
ANN ARBOR, MI, 48109
USA

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Anthony Grbic

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
REGENTS OF THE UNIVERSITY OF MICHIGAN
1109 GEDDES AVE, SUITE 3300
ANN ARBOR, MI 48109
USA

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14. ABSTRACT
The initial objective of this effort was to develop compact devices for controlling the phase and polarization properties of near-infrared radiation. These devices were to be based on cascaded subwavelength gratings consisting of high-contrast dielectrics—such as silicon and silicon oxide—and be fabricated using a local oxidation of silicon (LOCOS) technique. Following difficulties in fabricating multilayer structures using the proposed LOCOS technique, we investigated the design and fabrication of the cascaded grating structures using an additive manufacturing process (ceramic stereolithography) to enable monolithic fabrication without separate assembly or intermediate processing between layers. In ceramic stereolithography, an ultraviolet light source is used to selectively cure a photoreactive ceramic particle suspension layer-by-layer, resulting in a “green” part that is subsequently pyrolyzed and sintered to remove polymer components and leave a pure, dense ceramic structure. The process can produce high accuracy parts with small, high-contrast features that are well-suited to subwavelength patterning at microwave frequencies. Working closely with ceramic stereolithography manufacturers, we designed, fabricated, and experimentally characterized several broadband, multiband, and multifunctional polarization conversion devices for the technologically important Ku and Ka microwave frequency bands. We also investigated other varieties of all-dielectric metastructures, including an all-dielectric implementation of transmissive Huygens’ metasurfaces based on resonant ceramic rods embedded within a ceramic/air lattice. Using these concepts, we designed a metasurface-based, wide-angle-scanning dome antenna that steers beams towards the horizon while minimizing scan loss and validated the design using full-wave simulations.

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Swarm Security: Exploring the trade-offs between robot abilities and scale, swarm performance, and robustness to disruption

Abstract

The focus this year, given the 6 month delay to the start of the project, has been to build a good overview of the state-of-the-art, select an initial focus on the detection of faults in robot swarms using local metrics, and the implementation of preliminary simulations and results.

Accomplishments

Original project abstract

Swarm robotics allows for the deployment of large numbers of robots in applications ranging from search-and-rescue to environmental monitoring. Swarming relies on simple agents, reacting to their neighbours and local environment, resulting in emergent collective behaviours. The decentralised nature of swarms should, in theory, make them scalable to large numbers and robust to individual failure. Yet previous work has shown that failure of individual agents, whether due to defective hardware or malignant behaviour, could lead to poor swarm outcome. Disruptions include manipulating an agent's goal, its behaviour, the environment, or communication through the environment. Understanding how to make swarms resilient to such disruptions is key to their reliable deployment in reality, and their public acceptance.

Objectives and results this year

Due to a delay in hiring the PhD student (Suet Lee), we started this project 6 months late. Much of the focus of these first 6 months has been on background reading related to emergence, swarm robotics, and understanding how swarms can be made robust in case of faults. We also conducted a literature review on FDDR (fault detection, diagnosis and recovery, anomaly detection) for multi-robot systems and swarms in order to understand the work that has already been done. As a first research step we explored fault detection for swarms at the local individual level. This has involved developing a simulator with faults injected into the system and generating data for statistical analysis.

Major objectives: Understanding the state-of-the-art and refining the project objectives

What is safety?

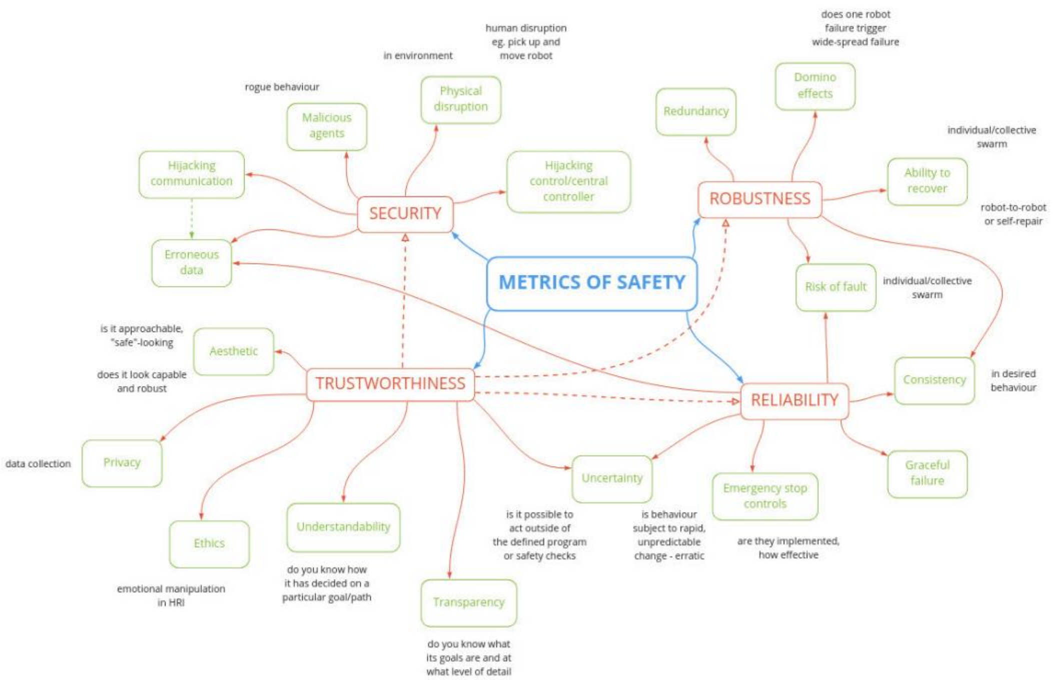
Safety is a key consideration for any system implemented in the real-world. It is a broad concept with many facets and the approach taken will depend on the system to be studied. Let us define a few of the concepts relevant to
safety:

• Safe: low probability of harm
• Trustworthy: honest, truthful
• Reliable: consistent in good performance
• Secure: protected against external attack
• Robust: able to withstand or survive adversity

These definitions make sense in the general context but we are interested in particular in the safety of swarm robotics which has its own set of challenges and attributes. The only definition in the above list which may be ambiguous in a swarm context is trustworthy – this concept might be better defined by asking the question: does the behaviour of the swarm meet our expectations? We will come back to the idiosyncrasies and challenges of swarms, but first let us analyze the concepts above in greater detail and how they relate to each other in a swarm context.

Our previous work (https://www.nature.com/articles/s42256-020-0213-2) provides a checklist for swarm safety - a list of considerations to be made for a swarm to be "safe". The figure below shows a mindmap with safety above the other four concepts, a parent "node", but there may not be a well-defined hierarchy. We can also consider metrics of safety, where metrics are defined attributes to be evaluated against certain criteria. Here the four child nodes could be considered as metrics of safety, each with their own sub-metrics on further sub-levels. For example, for robustness one can consider several metrics: risk of fault, redundancy, domino effects, consistency and ability to recover. Thus, one can produce a score for robustness based on the evaluation of these metrics.

In summary, we have narrowed down the concept of safety by defining metrics which can be used to evaluate a swarm quantitatively and as we see from the figure below, safety is a broad topic with many interesting avenues for exploration. For example, cybersecurity raises interesting issues with detecting malicious agents and simulating attacks on the system in a variety of ways. Trustworthiness may be more subjective and difficult to pin down as a concept, as mentioned previously. From a human trust perspective, there may be a focus on human-swarm interaction and the transparency of swarm behaviour. Given the existing work in our research group and externally, fault detection is a good starting point and in particular, for intralogistics using swarms in a warehouse scenario.



Fault detection

We focus on fault detection for swarms as a starting point. Robot swarms are increasingly deployed in real-world applications and making swarms safe will be critical to improving adoption and trust. They are usually characterized as being scalable and decentralized systems, meaning every robot is only able to react to its local environment. However, in taking these applications from a research environment to real-world implementation, there will need to be a consideration of safety and, in particular, a method to detect faults so they can be mitigated if needed.

Challenges

There are several challenges to implementing fault detection in a swarm context:

1. Swarms are decentralized in nature:

Faults will need to be detected based on local measures of the environment and the robot, using on-board sensing rather than an external central observer. This is not an obvious challenge to overcome as faults may cause different effects at different levels of the system (from the individual up to the swarm scale).

2. How to find the state of normal?

We would like to know the properties of a normally functioning robot. Any patterns which deviate from the normal state may indicate a fault not already accounted for. As a swarm of robots is a complex system, it may be hard to know how local behaviour and interactions propagate through the system.

3. How to identify whether a deviation from normal is truly a fault?

Consider a robot which has stopped moving, does it have a broken wheel or is it in an idle state, waiting before continuing its task? We do not have prior knowledge of data distributions for either scenario and this motivates a need to generate data for both the faulty and normal robot states, in order to differentiate between them.

Based on this background, we have decided to focus on the local level of a swarm: the challenges above give us several motivations for our study:

• We identify metrics which capture the local environment of the individual (motivated by challenge 1).

• We use a data-driven approach to extract metrics (motivated by challenge 2).

• We generate data to differentiate between the normal and faulty states of a robot (motivated by challenge 3).

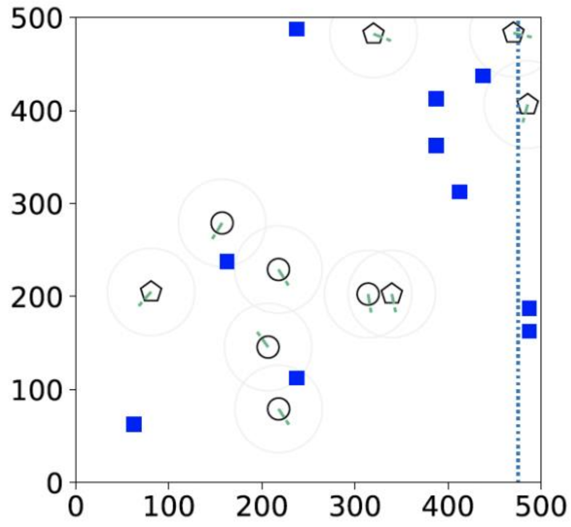
Initially, we will focus on an intralogistics problem with a homogeneous swarm retrieving and delivering boxes in a warehouse. This is an impactful, realistic use-case as there may be demand for out-of-the-box swarm solutions that can be deployed for small and medium enterprises. Previous work in our group has shown good performance in item retrieval using distributed control.

We will thus study the scenario in simulation: the robot model in simulation is modeled after the DOTS robot developed at our laboratory (https://arxiv.org/abs/2203.13809). The metrics we select are specific to our use-case but they may also capture more general properties of a swarm in any state. Our aim is to develop a new method for extracting metrics using a data-driven approach. The steps of the method are as follows:

1. We identify potential metrics and faults through a systematic analysis of the system.
2. We generate data for the system, injecting varying numbers of faults.
3. For each metric, we compute its statistical significance in differentiating between faulty and normal.

Major objectives: Swarm simulator for the fast extraction of fault detection metrics.

We are working towards a 2D simulation environment for the rapid extraction of fault detection metrics. The figure below shows the simulated scenario in python, and annotations to the simulator that allow us to easily monitor if fault detection is successful. Our scenario represents a warehouse: boxes are represented by blue squares, robots by circles. A green pointer shows the current heading. Grey circles around each robot indicate the camera sensor range. The drop-off zone is marked by a dashed vertical line on the right side of the arena. Pentagons show faulty robots.



Scripts have been produced to run hundreds of simulations with different faults injected to extract local metrics which will then be used to identify signatures of faults.

Dissemination

Suet Lee and Sabine Hauert have been active in outreach activities this year including the following.

Suet Lee played a central role in the International DOTS competition for swarm logistics hosted by our research group. She helped train and support teams, and produced blog posts to report on the results. https://robohub.org/simulations-real-robots-and-bloopers-from-the-dots-competition-powering-emergency-food-distribution-using-swarms/

She also attended the International Multi-robot systems (MRS) conference in Cambridge.

Sabine Hauert has further presented results of this project in the following invited talks.
KAUST, Swarm Engineering Across Scales, SA
TAS-RUSI, Swarm Engineering Across Scales, USA
Keynote Edinburgh CDT, Swarm Engineering Across Scales, UK

Plan for the year ahead

Our focus for the year ahead will be to use the data generated to automatically extract metrics useful in the detection of faults in swarms. We will the use these metrics to mitigate errors, and expand work to real-world DOTS robots.

Impacts

Development of the principal discipline(s) of the project
With this project, we aim to explore how to make swarms safe and robust by focusing on the local detection of faults and their mitigation.

Other disciplines:
As part of this work, we have also interfaced closely with another project focused on trustworthy swarms. This has led to joint work across both projects, including with ethicists, regulators, and researchers and from other technical disciplines.

Describe the impact in this reporting period on the development of human resources
Suet Lee, the PhD student on this project, has enjoyed a varied and rich research experience working within a smaller team focused on the warehouse scenario for swarm logistics, as well as participating in the broader swarm group at University of Bristol. She has also had the opportunity to work within the Trustworthy Autonomous Systems group (TAS), which focuses on the complementary property of trustworthiness.

She has also attended various workshops and seminars, the MRS 2021 conference, and supported the DOTS competition hosted by our research group, all of which have added to a rich research experience. As part of the TAS group, she is currently developing a framework for assuring the trustworthiness of swarm emergent behaviour within a team: Assurance of Emergent Behaviour for use in Autonomous Robotic Swarms (AERoS).

Describe the impact on teaching and educational experiences
Material from this project has contributed to Sabine Hauert's teaching in Bio-inspired AI.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
N/A

Impact on society beyond science and technology:
Building trustworthy swarms will be essential towards their deployment in real-world applications. This project lays the foundations for such deployments by highlighting ways in which swarms can be made trustworthy, how swarm behaviour can be specified for verification in the future, and how faults can be detected and mitigated.

Changes

Changes in approach
The fundamental objectives of the project have not changed. We decided however to use a newer, more sophisticated robot platform (DOTS) rather than the kilobots originally intended.

Problems or delays
We have not faced any challenges during this reporting period and the project is nicely on track.

Expenditure Impacts
We have not deviated in the expected spending. The only deviation was from hiring the PHD student on this project 6 months after the start of the project. We will therefore be requesting a 6 month no-cost extension to the grant so she can finish her PhD and produce the last papers of the project.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
N/A

Changes to the primary place of performance from that originally proposed
N/A

Technical Updates

We have included all papers and abstracts produced this year in attachment at the end of this document.

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!