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Design innovation of mesoscale robotic swarms: applications to cooperative urban sensing and mapping*

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Abstract: Development of mesoscale robots is gaining interest in security and surveillance domains due to their stealth and portable nature in achieving tasks. Their design and development require a host of hardware, controls, and behavioral innovations to yield fast, energy-efficient, distributed, adaptive, robust, and scalable systems. We extensively describe one such design and development process by: (1) the genealogy of our embedded platforms; (2) the key system architecture and functional layout; (3) the developed and implemented design principles for mesoscale robotic systems; (4) the various key algorithms developed for effective collective operations of mesoscale robotic swarms, with applications to urban sensing and mapping. This study includes our perception of the embedded hardware requirements for reliable operations of mesoscale robotic swarms and our description of the key innovations made in magnetic sensing, indoor localization, central pattern generator control, and distributed autonomy. Although some elements of the design process of such a complex robotic system are inevitably ad-hoc, we focus on the system-of-systems design process and the component design integration. This system-of-systems process provides a basis for developing future systems in the field, and the designs represent the state-of-the-art development that may be benchmarked against and adapted to other applications.

Key words: System-of-systems design; Mesoscale robot; Swarm; Urban sensing
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1 Introduction

Autonomous miniature robots offer numerous advantages, such as agility to access constricted spaces that are inaccessible to large robots or remote areas that are dangerous to humans, especially for urban sensing and mapping purposes (Dharmawan et al., 2018b). Their relatively minute footprints facilitate transportation and deployment; however, they can perform a host of collaborative swarming behaviors at a scale significantly larger than their own size (Dharmawan et al., 2018a).

Some of the challenges in developing miniature robots are dimensional restrictions of sensors or components (Dharmawan et al., 2017), the slender energy supply, and the processing capacity for autonomy. For instance, typical ranging modules used for robot's vision are usually bulky (Sundram et al., 2018). Specifically, for indoor surveillance and mapping, a GPS-denied localization technique with a low-power requirement and high accuracy is highly desirable (Nguyen et al., 2018).

Scalability is another salient feature to have in mesoscale robotic systems to augment their coverage, which can be achieved through having a swarm of miniature robots. A decentralized multi-robot system (MRS), whereby the computation, controls,

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and communications are carried out locally by the individual robot, is needed. It is highly fault-tolerant to the loss of multiple units at the expense of a more complex system. A decentralized swarm system requires a distributed communication network (Sekunda et al., 2016), a decentralized computing framework (Kit et al., 2018), and a cooperative control strategy (Zoss et al., 2018). To be effective, the implemented decentralized system and collaborative strategy need to be resilient under a varying number of robots (scalability), against the failure of individuals (robustness), and in reaction to an unknown dynamic environment (flexibility) (Bouffanais, 2016).

Being adaptive further elevates the merit of any robotic system. As the size constraint confines the functionality of a single miniature robot, having a heterogeneous MRS provides the added advantage (Vallegra et al., 2018) of adaptability through collective behavior by distributing diverse responsibilities to distinct robot species.

Taking the aforementioned desired features into consideration, three identified system-level challenges of developing mesoscale robotic swarms that we have been aiming to address through our works are designed for miniaturization, adaptability, and scalability. The key approaches that we have been developing in the past few years in an attempt to overcome these challenges, especially for urban sensing and mapping applications, are outlined in Fig. 1.

In the literature, most of the systems for swarming are developed with a focus on a homogeneous robot design. From a system-of-systems level design, we anticipate that the robot will undergo evolution in terms of both designs and capabilities. Hence, compared with the vast majority of existing swarm systems, our design approach is centered on the development of individual building blocks of the integrated swarm system, and the integrated swarm system is modular and more importantly platform-agnostic from the start. This approach enables us to continue designing, prototyping, and developing a range of robotic designs without compromising the final integration process.

To focus on the advancement of each of these efforts, we establish three different testbeds such that the evolution of one effort does not hinder others at the initial stage, but with the ultimate goal of converging towards a common platform. The three different testbeds, each mainly concentrating on a particular effort, are encapsulated in Fig. 2.

Miniaturization
• Magnetic sensing
• Ultra-wide band + barometer localization
• LiDAR mapping
Adaptability
• Swarm-enabling unit
• Central pattern generator control
• Modular design
Scalability
• Decentralized swarm
• Distributed communication
• Cooperative control

Fig. 1 Key challenges and developed solutions of mesoscale robots for urban sensing and mapping

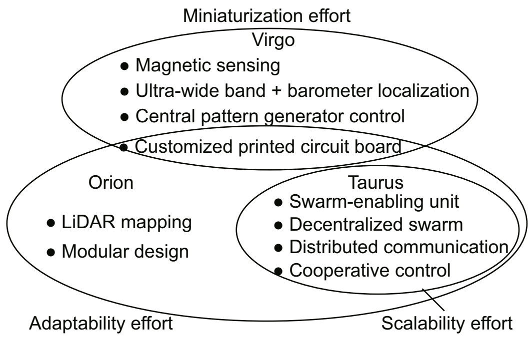

Fig. 2 Design genealogy of the testbeds

2 Design genealogy

Developing solutions to the three identified challenges, namely miniaturization, adaptability, and scalability, might impede the pace of individual progress if they are conducted on a single platform. For example, testing the autonomous swarm system for scalability is challenging when the sensor technologies being miniaturized are undergoing refinement. Likewise, evaluating the performance of the developed technologies is difficult when the modular platform designed for adaptability is evolving.

From this perspective, we thus use separate testbed architectures for different objectives, i.e., Virgo for miniaturization, Taurus for scalability, and Orion for adaptability. The use of multiple testbeds is an application of the design prototyping principle and strategy of "parallel prototyping," in which multiple design concepts are embodied and compared concurrently when flexibility exists in budget and where exploration has high potential value (Camburn et al., 2017b). It is likewise an adaptation of the theory of inventive problem solving laws of system evolution, in which there is uneven development of technologies within technical systems (Altshuller, 1984). Although each platform has its own unique role, the development of a certain technology can be centralized on other platforms if that architecture is deemed to be more suitable. Fig. 2 shows how the testbeds and developed technologies are interrelated with one another. The developed technologies are in fact platform-agnostic, and the Orion architecture itself would be the final common platform where all the technologies are integrated.

2.1 Virgo: miniaturization effort

The Virgo architecture seeks to design and develop miniaturized-base technologies to support the locomotion, sensing, and adaptive autonomy of the mesoscale robots. Base technologies imply the core foundations of the sensing and computation that will be used in the ultimate integrated architecture.

Virgo is a family of miniature spherical robots developed by the Singapore University of Technology and Design (SUTD) (Fig. 3). The system architecture of Virgo 3.0 comprises the top and bottom chassis, a printed circuit board (PCB), two DC motors, battery, and camera as its major components. The structure of a spherical robot is chosen as the testbed for the miniaturization effort as the spherical geometry presents a challenge to miniaturize the components to fit within the enclosing case. The architecture offers efficient omnidirectional planar mobility, while the outer shell provides natural dynamic dampening upon collision (Niu et al., 2014), exhibiting motion characteristics that are important during the experimental stage to push miniaturized technology development. Table 1 summarizes the evolution of Virgo components.

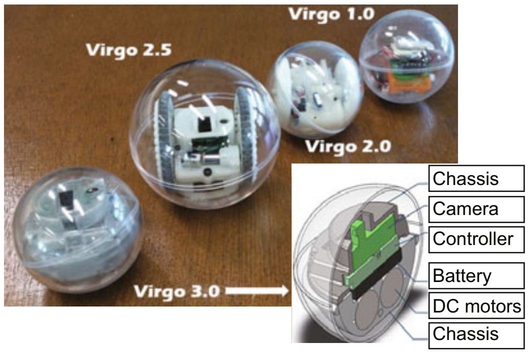

Fig. 3 Virgo, spherical robots developed by the Singapore University of Technology and Design (SUTD) (reprinted from Wu et al. (2017))

As commercial off-the-shelf electronic components are non-optimal for miniaturization, the first step of the miniaturization effort is to establish a customized PCB. To reduce the number of components required, system-on-chip technology has been harnessed to provide a solution where a microcontroller unit (MCU) is used, thereby saving valuable physical space and reducing energy consumption. As for Virgo 3.0, a customized next-generation 4-layer PCB with a physical footprint of 30 mm × 30 mm × 4 mm is designed (Nguyen et al., 2018), containing the following major components: STM32F411 32-bit ARM Cortex-M4 CPU, 9-axis inertial measurement unit (IMU), and motor driver (Fig. 4).

Using the base PCB, dead reckoning can be achieved by sensor fusion from the wheel odometry (for displacement) and the IMU (for bearing) (Ajay et al., 2015). Supplementary sensors can be easily added to the PCB to enhance both functionality and autonomy of the robot. To increase localization accuracy, especially in GPS-denied environments, we use ultra-wide band (UWB) modules and barometer, both of which are small in size and thus germane, and develop an indoor localization technique for the miniature robots.

For obstacle detection, we use the existing onboard three-axis magnetometer for depth sensing by

Table 1 Evolution of Virgo components

Version	Processor	Process clock rate	Size (mm)	Mass (g)	Battery life
Virgo 1.0	8-bit ATmega328 8-MHz CPU	15–20 Hz	60	46	0.4 h at full load
Virgo 2.0	32-bit ARM Cortex-M4 72-MHz CPU	750–800 Hz	60	50	2 h at full load
Virgo 3.0	32-bit ARM Cortex-M4 100-MHz CPU	>10 kHz	60	80	2 h at full load

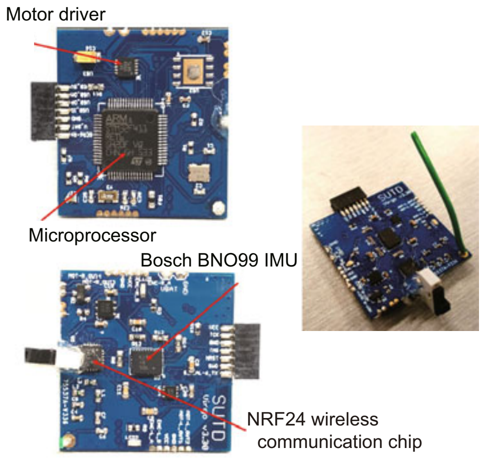

Fig. 4 Customized next-generation PCB design with ARM CPU, IMU, and motor driver

electrostatic detection (Wu et al., 2016). This approach has the advantage of using an existing component and keeping the overall footprint small. Thus, we work on developing a compact magnetic proximity sensor as part of the miniaturization effort on Virgo.

For the robot's vision, it has been found that common ranging modules are usually bulky (Sundram et al., 2018). Hence, we develop a custom-built light detection and ranging (LiDAR) module to reconstruct the point cloud of the environment for the miniature robots, thus enabling the real-time construction of an occupancy grid map (Kit et al., 2019). As the ranging module requires clear line-of-sight, it is impractical to develop it on Virgo. Thus, the miniature LiDAR mapping technology is developed directly on the Orion platform.

Various technologies developed in effort to further miniaturize the robot will be discussed in detail in Section 3.

2.2 Taurus: scalability effort

The Taurus platform allows for the development of efficient multi-agent distributed control algorithms to achieve biologically inspired swarming behaviors that will provide game-changing collective operations. The system architecture of the latest Taurus testbed comprises an XBee communication module, a Raspberry Pi single-board computer (SBC), real-time clock, power bank, and ultrasonic sensors (Fig. 5a). The collective of Taurus is expected to operate in a fully decentralized mode in terms of controls (collective decision-making), computation (information processing), and communication. Specifically, there is no central computing node; each individual agent handles all the data acquisition and global processing in a distributed and decentralized fashion. The robots are thus equipped with communication modules that enable them to communicate in a distributed mesh network by sending and receiving relevant data used by the swarming algorithm to produce a host of collective actions. A real-time clock is necessary to ensure that all the platforms are synchronized when communicating. To achieve this, the center of the development of Taurus is a swarm-enabling unit (SEU) (Chamanbaz et al., 2017).

As shown in Fig. 5b, the SEU is composed of a communication module and a processing unit that serves as a bridge between a particular robot and the collective. At the software level, each swarm is composed of three elements. The "body" controls the robot's movement and gathers information from its state and the sensed environmental data. The "network" is responsible for distributed communication to broadcast the current state of the agent to the swarm and to gather information from other agents' state. The "behavior" contains the decentralized cooperative control strategy.

By design, all the elements in SEU are independent of each other. For example, changing the

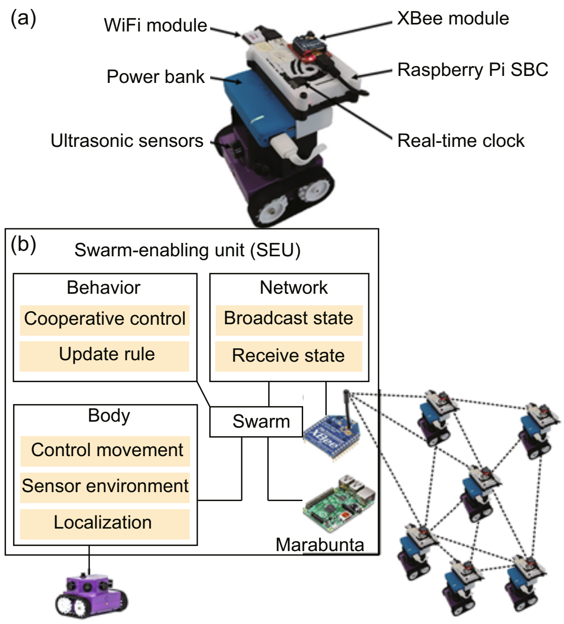

Fig. 5 Major components of the Taurus platform (a) and diagram of SEU (b) (reprinted from Chamanbaz et al. (2017), with permission from Bouffanais)

body element, i.e., the robot configuration and sensors, does not affect the distributed network configuration or the collective control strategy (vice versa). The SEU thus provides adaptability to the mesoscale robotic swarms by being platform-agnostic and is effortlessly integrated into other developed platforms with various sensors.

The decentralized swarm and the cooperative control strategy developed to equip the miniature robots with effective scalability will be discussed in detail in Section 3.5.

2.3 Orion: adaptability effort

The Orion platform design considers the prospect of flexibility to provide the adaptability required by differing environments, tasks, and applications for the miniature robots. The common system architecture of the Orion platform comprises chassis, reconfigurable wheel, and any additional optional sensor system (Fig. 6). Thus, the heart of Orion's development is the design exploration of reconfigurability and modularity of the platform.

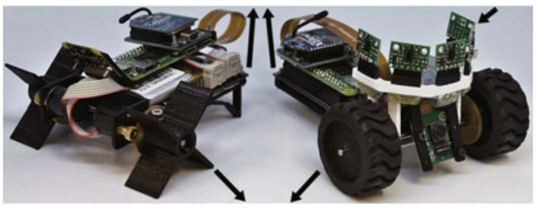

Fig. 6 Wall-climbing (O-climb) (left) and ground-mapping (O-map) (right) species of Orion with the major components labeled (reprinted from Kit et al. (2019), Copyright 2019, with permission from IEEE)

To achieve adaptability and heterogeneity for the miniature robots, the architecture of the Orion platform is classified into two parts: (1) the chassis, which is the main uniform element that would house the electronics and technologies developed by other platforms; (2) the wheels, which are reconfigurable depending on the requirements. There are two species of Orion developed for the specific application of indoor urban sensing and mapping: ground-mapping Orion (O-map) and wall-climbing Orion (O-climb) (Kit et al., 2019).

As shown in Fig. 6, the O-map units are equipped with rubber wheels and a ball caster for ease of mobility on various terrains, while the O-climb units have special wheel-legs with compliant adhesive tapes and a tail for robust climbing (Hariri et al., 2018; Dharmawan et al., 2019a, 2019b; Koh et al., 2019). Each species serves its specific functions in a heterogenous decentralized swarm using the homogeneous electronics and technologies while maintaining its miniature scale. The use case of the Orion platform's variants is described in Section 4. Table 2 summarizes the technical specifications of the two Orion species.

The adaptability of the miniature robots can be administered from a control perspective. We use a central pattern generator (CPG) as a feedforward controller to generate the desired robot locomotion in response to different environmental conditions (Chowdhury et al., 2017b). The developed adaptability control will be discussed in detail in Section 3.4.

2.4 Design unification

The shared goal of the three testbeds is to integrate them into a common platform and to establish a mesoscale robotic swarm system. Fig. 7 shows the system architecture, which consists of the energy flow of the hardware and the information flow of the software, when technologies of the three platforms are unified together. The Orion integrated system additionally includes a passive infrared (PIR) sensor and a camera for rudimentary urban sensing purposes. Urban sensing intelligence can be developed in the future using the information from these sensors. At the time of writing, Taurus technologies have been fully implemented into the Orion modular platform, while selected Virgo technologies have also

Table 2 Technical specifications of two Orion species

Species	Size (mm×mm)	Mass (g)	Structure	Capability
O-climb	100×82	137.5	Chassis, whegs, and vertical tail	Climbing 360° slope, internal transitions, and external transitions
O-map	120×100	203.4	Chassis, wheel, and caster ball	Waypoint navigation, obstacle avoidance, and mapping

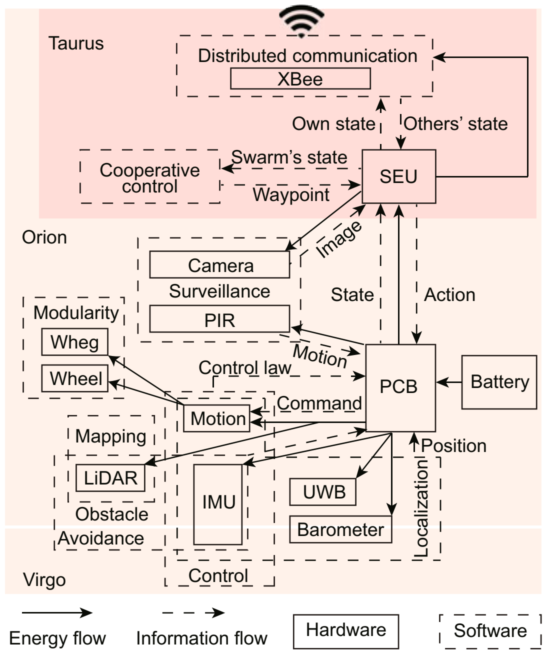

Fig. 7 System architecture of three mesoscale robots

Taurus has been fully implemented into Orion, while some of the Virgo technologies are in the process of being integrated

been implemented. Hence, the hardware and software listed within the Orion and Taurus portions in Fig. 7 summarize the components in the architecture of the integrated Orion system. Details of each of the individual building blocks of the unified design have been discussed in previous subsections and readers can refer to the respective subsections for details of the specific elements of the unified design.

With the current integrated system, we test the developed heterogeneous mesoscale robotic swarm to execute the multi-floor indoor mapping task in a real-world scenario. The performance of the multi-robot system in performing the task will be discussed in detail in Section 4.

3 Design solutions

In this section, we present and summarize the technologies that we have been developing towards constructing our autonomous mesoscale robotic swarm system.

3.1 LiDAR mapping

Conventional LiDAR systems consist of a single statically placed laser that emits and senses unit and scans across a certain field of view (FoV) via shooting laser beams through a rotating mirror that spans the FoV. They can measure long distances, in the range of 10–20 m; however, they are big, heavy, and of high energy cost for miniature robots. To overcome this, we custom design our own ranging module which consists of an array of five statically placed VL53L0X time-of-flight ranging sensors (Fig. 8a). The module is designed to achieve small footprint, weight, and voltage consumption. Due to the arrangement of the sensor array, the module can measure the depth information in front of the robot at a discrete interval of 45° up to a distance of 2 m. Fig. 8b shows a sample output of the LiDAR sensor as the robot travels through a rectangular space.

Using the in-house custom-designed LiDAR-based depth sensor array, we develop an algorithm to map the surrounding environment using a probabilistic mapping method. A two-dimensional (2D) space is divided into multiple grid cells, where each grid is assigned a posterior probability of occupancy, known as the occupancy grid. If the LiDAR sensor from the robot returns a distance value from a cell, the probability of occupancy of that cell will increase; otherwise, the probability of occupancy of the cell will decrease. When the probability of occupancy of a cell exceeds a certain threshold, the cell will be marked as occupied; otherwise, it will be deemed unoccupied. The unexplored cells will

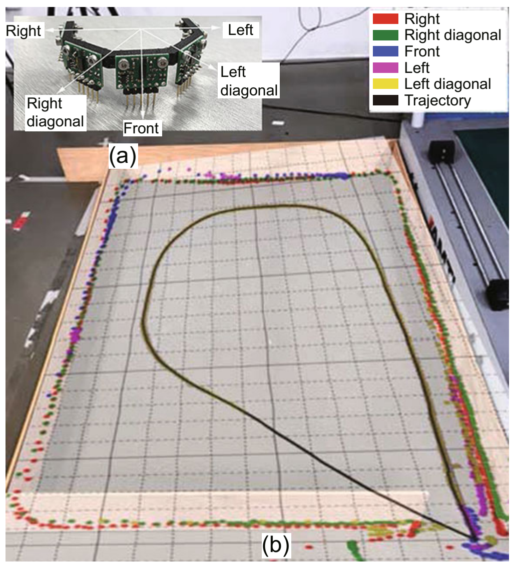

Fig. 8 Developed miniature LiDAR static sensor array for mapping (a) and LiDAR output with the robot's trajectory overlayed on a rectangular space (b) (reprinted from Sundram et al. (2018), Copyright 2018, with permission from IEEE)

References to color refer to the online version of this figure be assigned zero to the probability of occupancy. This approach is computed using the Bayes theorem, which takes in the robot location, reads from the LiDAR sensor, and returns the probability of occupancy. This approach also accounts for dynamic objects moving in the space. The custom-designed LiDAR sensor has been implemented and tested on the Orion platform, and the mapping performance has been reported by Sundram et al. (2018).

3.2 Magnetic sensing

Many indoor obstacles, e.g., furniture and walls, contain metallic components. A uniform magnetic field will deform around ferromagnetic elements. Considering this effect, we design a magnetic-based proximity sensor which can not only magnify the magnetic field but also detect the directional proximity of nearby ferromagnetic obstacles.

A highly spatially sensitive magnetic field can be created by placing two permanent magnets (PMs) with opposing magnetization close to each other. Subsequently, the three-axis magnetometer inside the IMU can be placed at the midpoint between two PMs, as depicted in Fig. 9a for Virgo, to measure the perturbation field as it approaches the ferromagnetic obstacles. Theoretical understanding of magnetic field perturbation has been discussed (Wu et al., 2016) and allows for the determination of the spatial pose (bearing and distance) of the object that causes this deformation. Design optimization in terms of dimensions of the PMs which provide the strongest detection and obstacle avoidance strategies has been devised (Wu et al., 2017). The proposed miniature magnetic based proximity sensor has been tested on the Virgo platform, and snapshots of the obstacle avoidance action of the robot are shown in Fig. 9b.

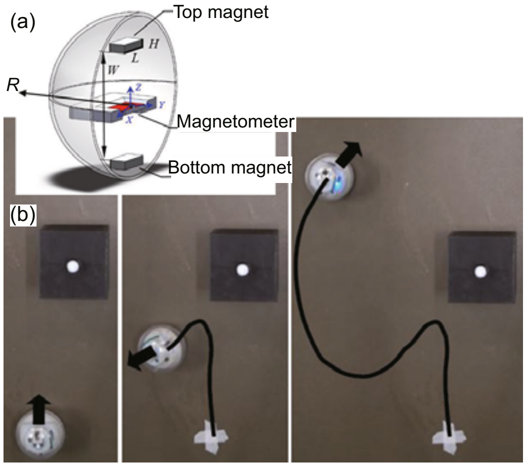

Fig. 9 Arrangement of the magnetic sensor array inside Virgo (a) and snapshots of the robot as it detects and avoids the obstacle (b) (reprinted from Wu et al. (2017))

3.3 UWB and barometer-assisted localization

With indoor urban sensing and mapping in mind, we explore the combinatory use of UWB modules and a barometer to increase the localization accuracy in GPS-denied environments. The time-of-flight principle can be used to estimate the distance between any two UWB modules as they transmit and receive messages. Similar to GPS, UWB localization employs trilateration to estimate the position of an object through the range measurements from the known UWB anchors' locations. A minimum of the three anchors is required to approximate a location on a 2D plane and four anchors for a three-dimensional (3D) position.

We explore sensor fusion from the wheel odometry, IMU, and UWB modules using an extended Kalman filter to localize the Virgo robot on a 2D plane, and acquire an improvement in the accuracy of localization (Nguyen et al., 2018). We extend the 2D trilateration of the UWB modules into 3D localization, and incorporate the reading from the barometer to further increase the accuracy of 3D localization (Goh et al., 2019). A novel horizontal projection model is proposed to reduce the computational complexity of 3D localization.

3.4 CPG feedforward control

Animals' locomotion is primarily composed of a variety of periodic motions. Biologists have named the phenomenon of generating rhythmic gaits the central pattern generator (CPG). By distributing each cycle into discrete and fast series of impulses, CPGs can generate high-dimensional rhythmic output gait signals as coordinated patterns when their input feeds are low-dimensional input signals and act like a feed-forward control policy, and the CPG control is useful in generating different kinds of patterned trajectories (Chowdhury et al., 2017b).

The CPG can be applied to robot's locomotion control. Applying CPG as the robot's feed-forward control involves developing the CPG model of the robot gait. We explore this approach for controlling the rolling motion of Virgo. Some CPG architectures upon which we have based our robot's gait model are Matsuoka-based architectures coupled with a non-linear oscillator (Chowdhury et al., 2017a) and a Hopf asymmetric non-linear oscillator (Chowdhury et al., 2018a). The mathematical models have a term which adds neuronal response of external disturbances (e.g., friction or noise) and is responsible for generating different kinds of patterned trajectories. For instance, we use our CPG model to generate a smooth surface gait for indoor environments (Fig. 10a) and a rough surface gait for outdoor environments (Fig. 10b), to optimize the resulting rolling gait trajectory based on the ground surface condition.

We then test the developed CPG model and feedforward controller on the Virgo platform by coupling the CPG model and feedforward controller with several feedback controllers, such as sliding mode control (SMC) (Chowdhury et al., 2017b), higher-order sliding mode control (HOSMC) (Chowdhury et al., 2017a), and adaptive sliding mode control (ASMC) (Chowdhury et al., 2018a), to render robustness against external disturbances and parameter uncertainties. The feedforward-feedback control strategy regulates the stability of the rolling angle and hence the rolling motion of the robot. Figs. 10c and 10d show the samples of the resulting error of the roll angle for the CPG model coupled with SMC and HOSMC (Chowdhury et al., 2018b). As shown in Figs. 10c and 10d, the developed CPG-based controller can stabilize the robot's roll angle during motion on two different surfaces by adaptively changing the feedforward trajectory.

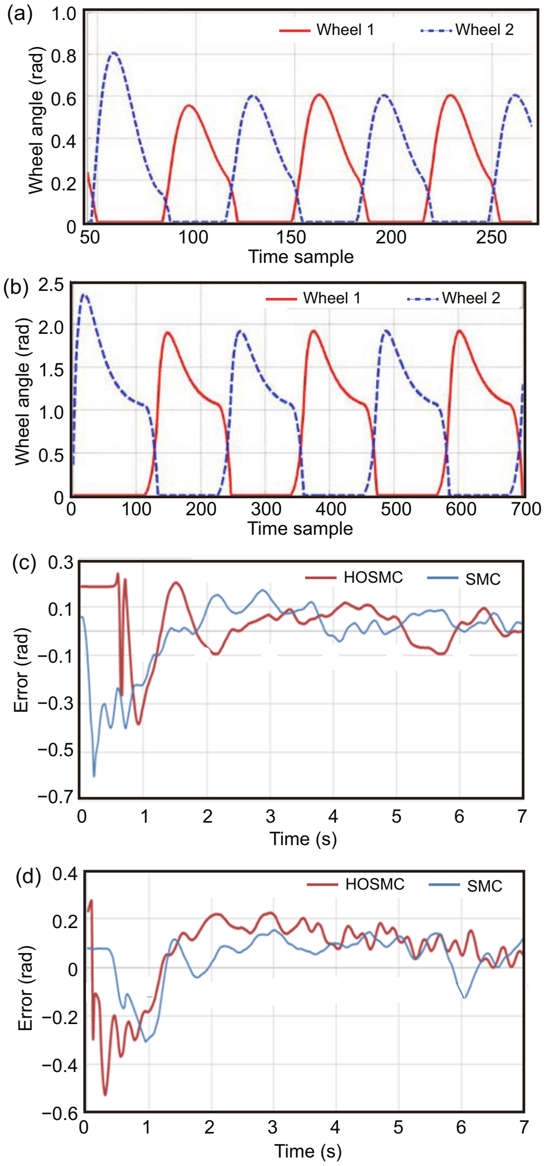

Fig. 10 CPG generated gaits and control implementation results: (a) rolling gait for the smooth surface; (b) rolling gait for the rough surface; (c) error signal for the smooth surface; (d) error signal for the rough surface (reprinted from Chowdhury et al. (2018b))

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3.5 Decentralized swarm system

To equip the mesoscale robots with scalability, we use and develop a decentralized swarming technology, so that the flock of the miniature robots can collectively operate under a wide range of swarm sizes. Distributed communication networks and cooperative control strategies are the paramount elements of a scalable, robust, and flexible decentralized swarm operation.

To grant the mesoscale robots with the abilities of communicating in a distributed fashion and establishing a dynamic (switching) communication network where nodes can be added or subtracted during operations, we equip them with XBee PRO modules that can create a distributed mesh network which automatically reconfigures itself as the agents move and enter/leave each other's communication range (Zoss et al., 2018). The dynamic topology of the wireless ad-hoc network formed by the onboard XBee modules can be tuned to achieve an optimal collective performance, for instance, when subjected to local perturbations (Mateo et al., 2019).

As a collective, the swarm system should operate towards common global objectives. These global objectives have to be mapped into individual and agent-specific commands: an operation instigated by the cooperative control strategy and the approach it takes determine the effectiveness of the large-scale collective behavior of the system. To achieve a decentralized operation working under distributed communication, we impose spatial and temporal locality to the cooperative control strategies; that is, the action of an agent is solely determined by the information gathered on a certain current neighborhood of its location. These conditions are implemented by considering iterative update rules that control the trajectory of an agent. We explore different cooperative control strategies for diverse global objectives, such as consensus, perimeter defense, environment exploration (Chamanbaz et al., 2017), collective behavior, collective navigation, area coverage (Zoss et al., 2018), and frontier-based exploration (Kit et al., 2019). These behavioral rules can be agent-specific, and at any given time different agents may be following different rules.

Fig. 11 shows an example of how an agent following a collective navigation strategy can reach a target when a group of flocking agents are in the way (Zoss et al., 2018). The rest of the agents can move around their equilibrium position to open up space for the single agent as it travels through (Fig. 11a). The flocking group can also remain stationary while the moving agent circumvents the agents in the flocking group to reach the goal (Fig. 11b). Alternatively, the moving agent can simply pass through the collective to reach its goal (Fig. 11c).

3.6 Summary of technologies

In this subsection, we summarize the accomplishment of the technologies that we have described to address the identified challenges of the mesoscale robotic system. In terms of minizaturization, Table 3 summarizes the the dimensions of the technologies as well as the mass of the technologies if added into a mesoscale robot.

In terms of adaptability, Fig. 12 summarizes the modularity of the developed miniature robots. From a software perspective, the SEU enables the adaptability of the network, behavior, and body elements. The modular locomotion and the easy add-on sensors provide the adapatability to the hardware.

In terms of scalability, we test our developed decentralized swarm with different numbers of units. Table 4 summarizes the largest number of robots used for each of the work. The largest number of agents we have tested physically to date is 45.

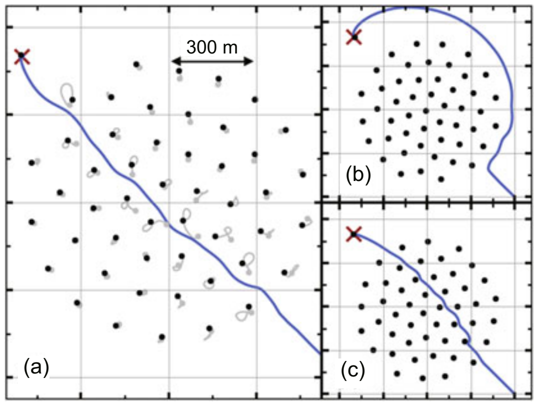

Fig. 11 Simulation of the possible swarm behaviors
A group of agents aggregate following the flocking strategy. An additional agent is directed by the collective navigation strategy towards a goal (cross mark). Depending on the parameters of the cooperative control strategies, the swarm can execute group yielding (a), bypassing (b), and sneaking (c) behaviors (reprinted from Zoss et al. (2018), with permission from Bouffanais)

Table 3 Summary of miniaturization effort

Technology	Size (mm×mm×mm)	Mass (g)
LiDAR mapping	60×40×20	4.75
Magnetic sensing	12.7×12.7×6.35	7.75
UWB (2D) localization	23×13×2.9	1.40
UWB + barometer (3D) localization	21.6×16.6×3	1.20

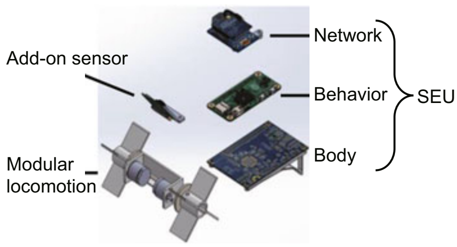

Fig. 12 Summary of adaptability effort depicted on O-climb

4 Use case

In this section, we illustrate the use of our developed decentralized and heterogeneous mesoscale robotic swarm, whose hardware and system architecture are depicted in Figs. 6 and 7 respectively, to execute a multi-floor mapping task in real-world settings. The collective is tasked to map two floors of unstructured and dynamic environments in one of our campus buildings during office hours (Kit et al., 2019). Eight O-map units are positioned on one floor (F1), and four others on the floor above (F2). Two O-climb units are placed on a vertical wall and ascended during the experiments, thereby expanding the distributed communication network between floors, as well as sensor-based surveillance capability from a height vantage point. The layouts of the surface areas to be mapped on F1 and F2 are shown in light gray in Fig. 13, and they consist of open spaces, lift lobbies, and office rooms with open doors. As seen from the discrete snapshots in Fig. 13, using the exploration cooperative control strategy, the mesoscale robotic swarm can diverge favorably even when all of them start from the center of the space and cover the required spaces to be mapped within 3–4 min depending on the dynamic obstacles encountered.

Table 4 Summary of scalability efforts

Reference	Number of agents
Mateo et al. (2019)	11
Kit et al. (2019)	12
Vallegra et al. (2018)	22
Zoss et al. (2018)	45
Chamanbaz et al. (2017)	45

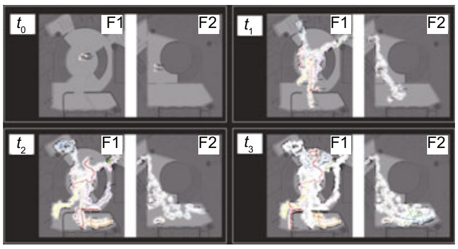

Fig. 13 Snapshots at successive time instants (t_0, t_1, t_2, and t_3) of the mapped areas by 12 units across two floors (F1 and F2) (reprinted from Kit et al. (2019), Copyright 2019, with permission from IEEE)

References to color refer to the online version of this figure

5 Discussion: design insights on mesoscale robotic systems

In this section, we concisely review the insights that we gathered during the process of developing our mesoscale robotic swarm systems. Table 5 outlines the identified design principles based on our experiences, observations, and extensive testing work on the development of mesoscale robotic systems, and the respective references that the subject was implemented to or concluded from. These principles follow an imperative form (formalism) and are stated as prescriptive actions (Fu et al., 2015, 2016), whereby a principle, in this sense, is "a fundamental rule or law derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution." In this case, the focus is on the development of innovative mesoscale robotic systems. Justification of the principles and their use and extendibility is provided in the last column of Table 5 in the form of foundational supportive references.

Following the design principles, our work approaches the development of swarm systems from a system-of-systems level design, whereby we modularize the development of different focus functions (miniaturization, scalability, and adaptability) and have them developed in parallel and platform-agnostic. This has benefited us by being able to independently add functions to or subtract functions from the swarm system, thus having a fully functioning heterogeneous swarm for testing alongside the development of individual building blocks. It has been shown through our various works (Table 4)—and including this one—that SEU can be used on multiple different robotic platforms, such as surface vehicles, ground robots, and climbing and rolling robots, thus having different hardware configurations and capabilities.

The swarm-inspired design principles and specifically cooperative control algorithms are devised to ensure the effective collective operations without the need for a reliable and permanent communication channel between all participating units. The behavior of each individual platform at any instant is governed by its current state and the state of neighboring units in the network sense. Hence, this requires only short-range local communications. Nonetheless, during the development phase and experimentation, it is often beneficial to have a more refined control system, and this explains our use of a monitoring station connected through the ad-hoc network to the swarm for our multi-floor

Table 5 Design principles for mesoscale robotic systems

Category	Design principle	References for development or application	Foundational supportive references
Mesoscale robotic system-of-systems architecture and components	**Compact components**: For the purpose of miniaturizing and increasing system performance, reduce the size and mass of components through optimization and new technology development	Niu et al., 2014; Ajay et al., 2015; Dharmawan et al., 2018a; Sundram et al., 2018	Singh et al., 2009; Weaver et al., 2010
Mesoscale robotic system-of-systems architecture and components	**Low power consumption**: To achieve system performance in terms of duration and longevity, reduce power consumption of components, subsystems, and the overall systems through optimization, elimination of leakage or unnecessary functionality, and intelligent energy management	Kit et al., 2018; Nguyen et al., 2018; Dharmawan et al., 2019a	Qureshi et al., 2006; Keese et al., 2007; Tilstra et al., 2015
Mesoscale robotic system-of-systems architecture and components	**Modularity**: For the purposes of system flexibility and reconfiguration, localize or increase the modularity of the system by: (1) separating modules to carry out functions that are not closely related; (2) confining functions to single modules; (3) confining functions to as few unique components as possible; (4) dividing modules into multiple small and identical modules; (5) collecting components which are not anticipated to change in time into separate modules; (6) collecting parts that perform functions associated with the same energy domain into separate modules	Hariri et al., 2018; Kit et al., 2019	Stone et al., 2000; Qureshi et al., 2006; Keese et al., 2007; Singh et al., 2009; Weaver et al., 2010; Tilstra et al., 2015
Mesoscale robotic system-of-systems architecture and components	**Collaborative swarm**: To increase the scalability and performance profile of mesoscale robotic systems, develop decentralized communication in a distributed network and adopt cooperative control by sending and receiving relevant data used by a swarm to produce a host of collective actions	Chamanbaz et al., 2017; Zoss et al., 2018	
Mesoscale robotic system-of-systems architecture and components	**Heterogeneity**: For the purpose of adaptability, develop system alternatives or complementary architectures with diversification in states, functionality, or reconfigurability	Vallegra et al., 2018; Kit et al., 2019	
Design process of mesoscale robotic systems	**Parallel systems testbed & prototyping**: For the purposes of lean development and reduction of cycle time development, explore multiple parallel systems as a genealogy with multiple species and subspecies	Wu et al., 2017; Hariri et al., 2018; Sundram et al., 2018; Kit et al., 2019	Moe et al., 2004; Ries, 2011; Blank, 2013; Camburn et al., 2017b; Lauff et al., 2017, 2018
Design process of mesoscale robotic systems	**Uneven development of technologies**: For the purposes of resource use and critical technologies innovate, create multiple testing platforms as the latency time of development for technologies for technical systems will be different and uneven	Wu et al., 2017; Nguyen et al., 2018; Vallegra et al., 2018	Altshuller, 1984; Moe et al., 2004; Camburn et al., 2017b Lauff et al., 2018
Design process of mesoscale robotic systems	**Innovation and creativity for mesoscale robotic systems**: Due to technical conflicts and contradictions and the frontier nature of mesoscale robotic systems development, choose key knowledge domains and subsystems for innovative and creative solutions development, applying methodologies in discovery and design innovation	Chowdhury et al., 2017a, 2017b; Dharmawan et al., 2017; Wu et al., 2017; Chowdhury et al., 2018a, 2018b; Goh et al., 2019; Koh et al., 2019	Camburn et al., 2017a; Luo and Wood, 2017; Luo et al., 2017; Sng et al., 2017; Venkataraman et al., 2017; Luo et al., 2018
Design process of mesoscale robotic systems	**Lean development of new technologies and architectures**: For the purpose of lean development of mesoscale robotic systems, adapt DIY maker and fabrication principles such as repurposing off-the-shelf components and subsystems, standardizing fabrication processes, and satisficing component quality	Niu et al., 2014; Chamanbaz et al., 2017; Nguyen et al., 2018; Sundram et al., 2018; Goh et al., 2019	Ries, 2011; Blank, 2013; Camburn et al., 2015; Camburn and Wood, 2018
Design process of mesoscale robotic systems	**Design innovation with additive manufacturing (DIwAM)**: To quickly develop system components, subsystems, and physical architectures, and to manage complex geometries, reduction of components and fasteners, and reduction of mass, employ additive manufacturing processes and principles and topology optimization in the development of mesoscale robotic systems	Ajay et al., 2015; Dharmawan et al., 2018b; Kit et al., 2019; Koh et al., 2019	Cho et al., 1998; Dutson and Wood, 2005; Perez et al., 2015; Perez, 2018; Perez et al., 2019

mapping experiment discussed in Section 4. This station gathers all the information available from all participating agents. This level of control can be easily achieved with the XBee PRO modules equipping the mesoscale robots. As mentioned earlier, these modules can build a dynamic and global routing network, such that messages can be sent from the base station to any specific unit, even if it is out of the range of direct communication.

The real-world scalability of our swarm system has been tested using up to 45 devices. Although this number might still be rather low, given the decentralized nature of the system design, its scalability is expected to hold for a significantly larger number of agents, provided that the distributed communication strategy can be scaled accordingly (Zoss et al., 2018). Moreover, swarm systems with more than 100 units (all the way to 1024 for the kilobot (Rubenstein et al., 2014)) are essentially operating with extremely simple and basic robotic units, and their collective operations are indeed exceptional scientific "tour de force." However, when considering actual engineering swarm systems tasked with performing "useful" collective operations in unstructured dynamic environments, there are very few swarm systems reported with more than 10 units. This is particularly true when considering systems operating in the absence of any supporting infrastructure (e.g., overhead localizing cameras and a central computer for control purposes). In that respect, we believe that our swarm system with its truly decentralized architecture and more than 10 units is state-of-the-art.

6 Conclusions

Mesoscale robotic swarms are attractive due to their portability and scalability. The complexity of the systems poses numerous challenges to their development. In this study, we have consolidated and summarized our diverse effort and accomplishments in developing mesoscale robotic swarm systems. The challenges that we aim to address have been identified, and the various devised solutions have been concisely explained. The design genealogy and system architectures of the robotic platforms alongside the evolution and integration of the technologies have been presented. The real-world demonstration has illustrated the practicality and functionality of the developed technologies. Ultimately, the key design principles that are discovered and learned throughout the course of developing the mesoscale robotic swarm systems have been discussed.

Our cooperative control strategies are usually pre-defined and formulated by users depending on the swarming goal. The agents are not yet equipped with the capability of independently switching or generating update rules. Building up from this work, in the future, we are interested in developing a highly intelligent swarm system with an individual agent capable of deciding independently which rule to apply and creating new rules given the individual agent current state to achieve a more complex global objective.

Compliance with ethics guidelines

Audelia G. DHARMAWAN, Gim Song SOH, Shaohui FOONG, Roland BOUFFANAIS, and Kristin L. WOOD declare that they have no conflict of interest.

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