Audelia G. DHARMAWAN, Gim Song SOH, Shaohui FOONG, Roland BOUFFANAIS, Kristin L. WOOD, 2019. Design innovation of mesoscale robotic swarms: applications to cooperative urban sensing and mapping. *Frontiers of Information Technology & Electronic Engineering*, 20(12):1618-1631. https://doi.org/10.1631/FITEE.1900384

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

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

Corresponding author: Gim Song SOH
E-mail: sohgimsong@sutd.edu.sg
ORCID: http://orcid.org/0000-0002-0042-5151

Motivation

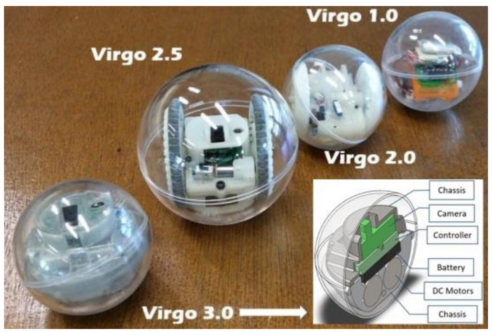
- Autonomous miniature robotic swarms offer numerous advantages, such as the agility to access constricted spaces that are inaccessible to large robots or remote areas that are dangerous to humans. Identified challenges of developing such systems include miniaturization, adaptability, and scalability.
- 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.

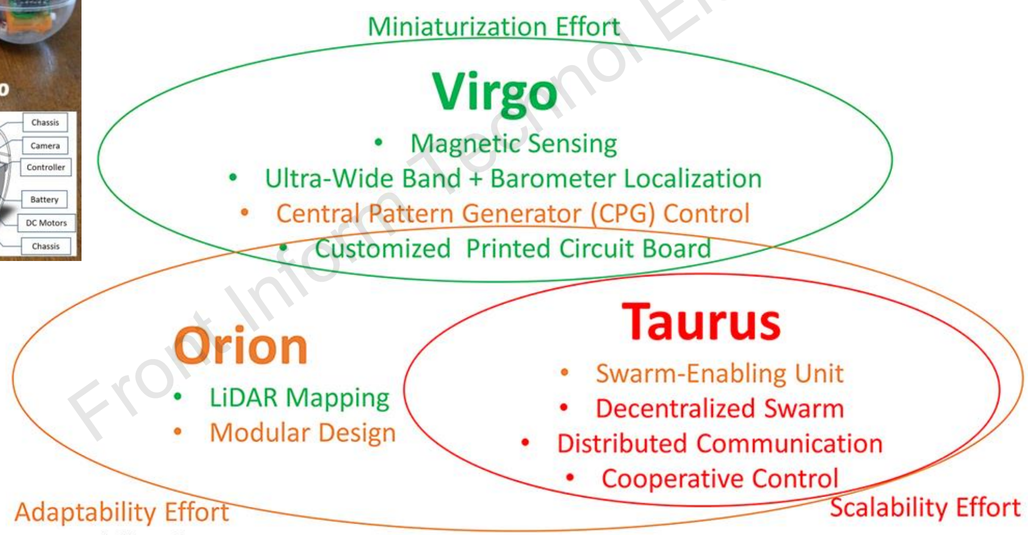
Main idea

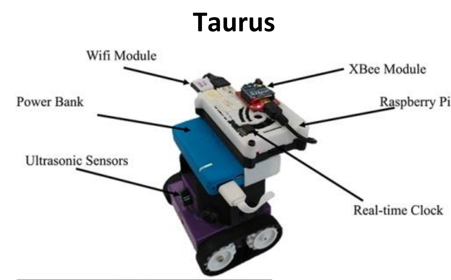
- Our design approach is centered on the development of individual building blocks of the integrated swarm system, which is modular and platform-agnostic. This enables us to continue designing, prototyping, and developing a range of robotic designs without compromising the integration process.
- To focus the advancement of each of the identified challenges, 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.

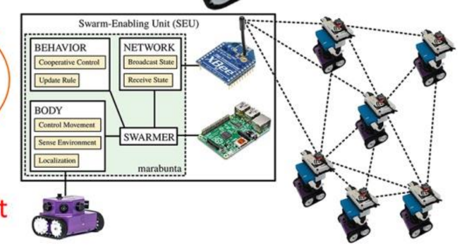
Method

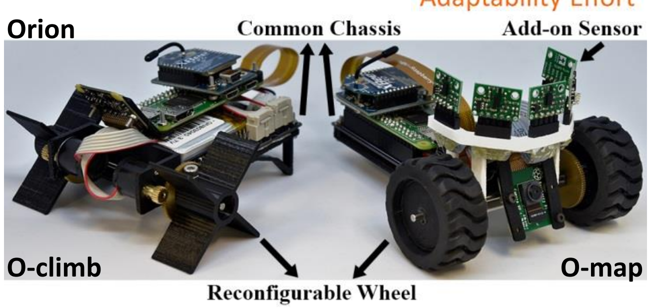
1. Design genealogy of the testbeds and the developed solutions











2. System architecture of the unified testbeds, with modular and platform-agnostic functions

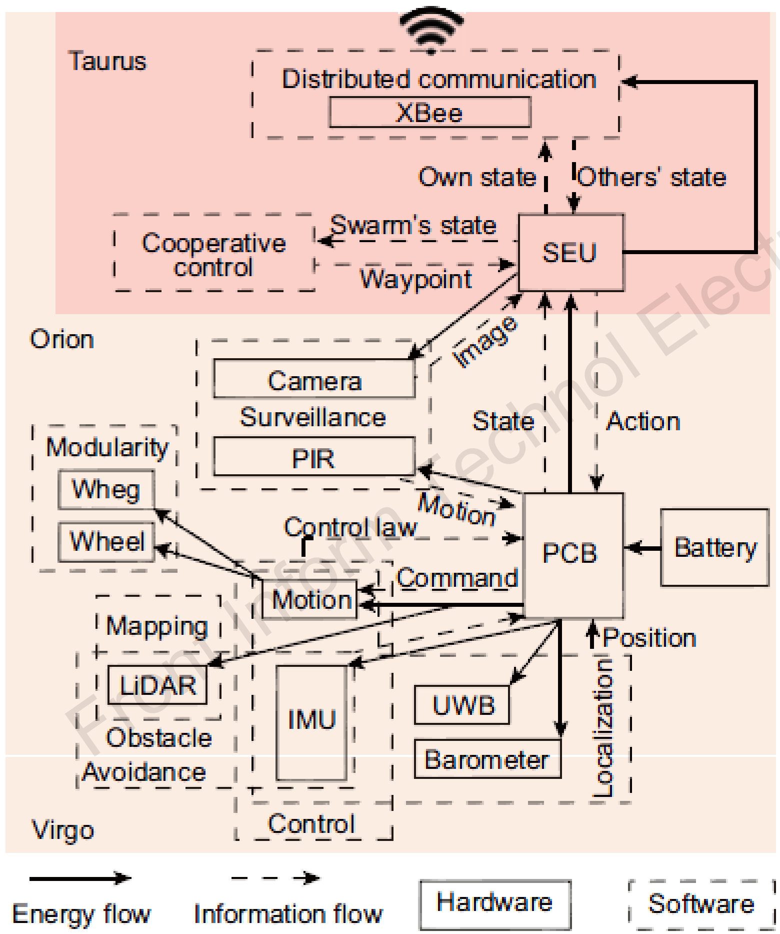


Fig. 7 System architecture of three mesoscale robots

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

Major results

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

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

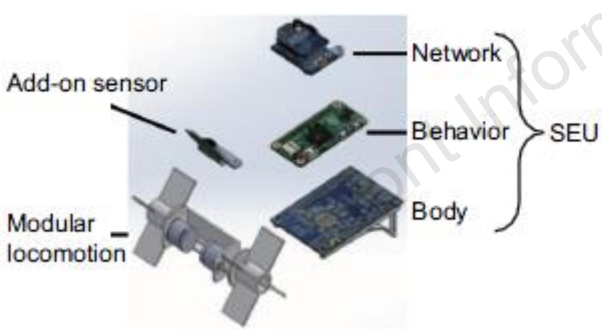


Fig. 12 Summary of adaptability effort depicted on O-climb

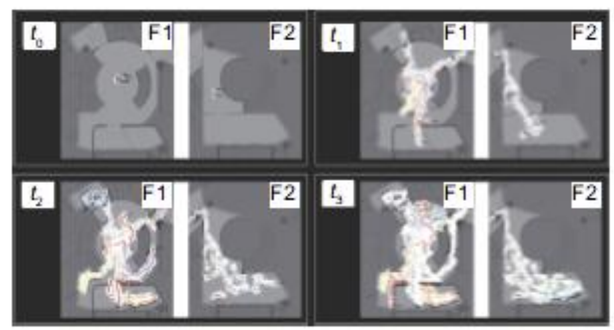


Fig. 13 Snapshots at successive time instants (t_0, t_1, t_2, and t_3) of the mapped areas by 12 units across two floors (F1 and F2) (reprinted from Kit et al. (2019), Copyright 2019, with permission from IEEE)

References to color refer to the online version of this figure

Major results (Cont'd)

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
	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
	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
	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	
	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	

To be continued

Major results (Cont'd)

Continued

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
	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
	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
	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 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

Conclusions

- 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.
- The key design principles that are discovered and learned throughout the course of developing the mesoscale robotic swarm systems have been discussed, and real-world demonstration has illustrated the practicality and functionality of the developed technologies.