International Journal of Engineering & Technology, 7 (2.21) (2018) 20-23

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Swarm-dular quadcopter: bringing swarm robotics and modular robotics together

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Abstract

In this paper, we present a new concept in robotics, which we call as swarm-dular robotics, by bringing together swarm robotics and modular robotics. We propose a swarm-dular quadcopter, which is a modular quadcopter, where, multiple wheeled ground robots (AGVs), which are part of a heterogenous swarm or multi-robotic(agent) system (MRS or MAS), attach/dock together to form an aerial quadcopter robot. We provide a conceptual design and demonstrate the proposed system using simulation experiments in Robot Operating System (ROS). Behavior of the system as both a swarm and a modular quadcopter UAV are demonstrated.

1. Introduction

Modular robots belong to a family of robots, where individual modules, with limited functionality, physically combine (or dock) together to form a functional robot. This concept was first proposed in the late 1980s [1]. Since then, this field of robotics has been attracting many researchers. Gilpin and Rus [2] provide a review of the literature on modular robots, and a more recent review is provided in [3]. It can be observed from the classification of modular robots provided in [3], that the most modular robots configure into a manipulator, while individual modules have limited or no individual functionality. Further, functionality of the configured robot has also not been discussed much in the literature except for improved motion capabilities such as in Modred [4]. Also, most of the modular robots have been restricted to ground robots except for distributed flight proposed by [5]. However, the individual modules in [5] combine together only to fly together, rather than configure into a meaningful individual such as an UAV, though the modules have this capability.

While in a modular robot the individual modules physically attach (or dock) to each other to form a functional modular robot, in swarm robotics or multi-robotic (agent) systems (MRS/MAS), individual robots cooperate to achieve a complex task. The concept of swarm robotics was introduced in early 1990s[6]. The swarm robotics, finding its inspiration from swarm of bees, flock of birds, school of fish, etc., abundant in nature, deals with multiple cooperating robots where individual robots act based on the actions of the neighboring robots, leading to a useful collective behavior. An individual robot in a swarm, unlike in modular robots, is a fully functional robot by itself. A closely related field is of cooperative robotics, where robots may physically interact, resulting in temporary loss of some degrees-of-freedom of the individual robots. Examples are cooperating manipulators operating on a same work piece, or a group of robots transporting an object. Though a swarm of robots may act cooperatively in this sense (cooperative transport, for example), typically, members of a swarm interact and cooperate only by exchanging information, or observing other members of the swarm using onboard sensors, and plan their action based on this information, rather than physically attaching or docking resulting in temporary loss of some degrees-of-freedom of the individual robots.

There are a few attempts of bringing swarm/cooperative robotics and modular robotics together. In [7], authors use members of heterogeneous swarm, called the swarm-bots, as modules, which depending on the need attach together to enhance their capabilities. The approach is more close to cooperative robotics than to modular robotics. Here one or more swam modules assist, or transport another module by attaching to it physically. Another closely related work is proposed in [8]. Here, the modules which can act as basic manipulators individually, controlled by a central module, configure into a functional AGV, called a SMC-rover, after combining with a central module. Though the work does not explicitly mention the swarm behavior of individual modules, it has a limited capability to act as both a swarm of robots (manipulators) and a modular AGV.

Aerial robots (UAVs) have been used in applications such as disaster management [9], search and rescue [10], [11], etc. In this paper, we combine concepts from swarm robotics and modular robotics, to propose a new field of robotics that we call as swarm-dular robotics. We then present a swam-dular quadcopter, a modular quadcopter UAV concept, where, members of a heterogeneous swarm of AGV configure into a modular quadrotor.

2. Swarm-dular robotics

Consider a cooperative search and rescue operation using multiple (swarm of) robots. Aerial robots (UAVs) such as quadcopters are best suited for aerial survey of the affected area. Ground robots (AGVs) are more suitable for a closer view. Further, AGVs can reach regions which may not be accessible to UAVs. Hence, a heterogeneous swam or group of cooperating AGVs and UAVs are more effective in such an application.

Now consider a situation, where a heterogeneous group of AGVs are employed. A few individual members of the swarm combine together to configure into another AGV or a UAV as in modular robotics. This results in a heterogeneous swarm of individual

AGVs, and UAVs which are formed out of some of the AGVs themselves. Now we propose a new field of robotics which we call as swarm-dular robotics, bringing together swarm robotics and modular robotics. A swarm-dular robot is a family of individual robots called swarm-dules. A swarm-dule acts both as member of a swarm and a module, which can configure into a modular robot by combining with other swarm-dules. Like any member of a swarm of robots, swarm-dules are fully functional robots, and when combined with other swarm-dules, they lose individuality (including some degrees-of-freedom), and configure into a swarm-dular (modular) robot. Distinctive features of modular robotics, cooperative robotics, swarm robotics (or MRS/MAS), and the proposed swarm- dular robotics are listed in Table I. It can be clearly observed that swarm-dular robotics is a perfect combination of swarm and modular robotics. Next we propose a modular quadcopter as a demonstration of the proposed swarm-dular robot concept

Fig. 1: A quadcopter has four rotors at four corners and a central control unit

3. A Swarm-dular quadcopter

A quadcopter (or a quadrotor) shown in Figure 1 has rotors along with corresponding brushless DC (BLDC) motors at four corners, and the control unit at the center. The rotors face upwards and the quadcopter motion, position and orientation can be controlled by controlling the speeds (and the direction) of the individual rotors. This coordinated control is achieved by the control unit. There is a natural modularity in its design. We can consider the quadcopter to consist of four peripheral modules which primarily carry the rotors along with BLDC motors, and a central module housing the central unit, as illustrated in Figure 2. This motivated us to conceptualize a modular quadcopter.

Table I: Comparative Features of Modular, Cooperative, Swarm, and the Proposed Swarm-dular Robotics

Type of robot	Individual member	Individual functionality	Interaction details	Final outcome
Modular	Modules	no/limited	- Modules physically attach or dock to each other. - loss of d.o.f of individual modules. - modules loose individual existence.	A Configured robot
Cooperative	Robots	Fully functional	- Physically attach to or contact other robots. - Leads to temporary loss of d.o.f individual robots - robots may partly loose individual existence.	Perform a complex task
Swarm	Robot	Fully functional	- No physical attachment to other robots - Interaction only through sensors and/or communication. - No loss of individual functionality or d.o.f. - Robots do not loose individual existence.	Collective behavior
Swarm-dular	Swarm-dules	Fully functional	- Can function as a swarm - Swarm-dules physically attach or dock to each other. - loss of d.o.f of individual modules. - swarm-dules loose individual existence.	- Collective behavior - A reconfigured Swarm-dular robot

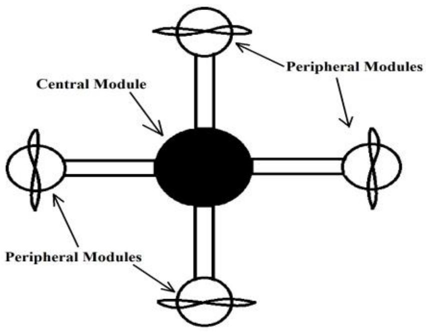

Fig. 2: A quadcopter can be thought of a made up of four peripheral modules containing the rotors and a central module housing the control unit

Conceptual design

The swarm-dular quadcopter proposed in this work has two types of swarm-dules (modules), namely, peripheral swarm-dules, and central swarm-dules. A central swarm-dule along with four peripheral swarm-dules can configure into a quadcopter. A central swarm-dule has four docking stations to which four peripheral swarm-dules dock. On docking, the whole unit functions as a quadcopter and individual swarm-dules lose their identity as well as degrees of freedom. Further, each of the swarm-dule can function as AGVs individually and be part of a heterogeneous swarm of robots. While individual swarm-dules operate as AGVs in ground mode, the docked system operates as an UAV in the aerial mode.

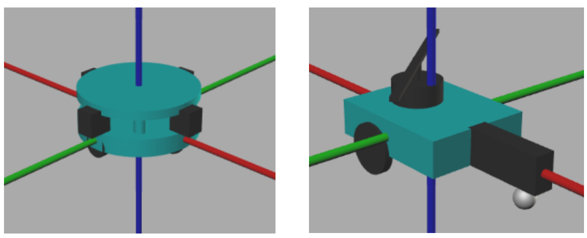

Fig. 3: Conceptual model of (a) the central swarmdule and (b) the peripheral swarm-dule in ROS

Central swarm-dule: The central swarm-dule, which functions as an AGV in ground mode, acts as the brain in the aerial mode. The central swarm- dule houses two different controllers in it, one each dedicated to the control the aerial mode, and the ground mode of operations. The aerial mode controller is basically a flight controller. A pair of motors with differential drives along with a castor wheel are used for the movement in ground mode, along with other necessary sensors, and communi- cation systems. A conceptual design within the ROS environment is shown in Figure 3 (a).
Peripheral swarm-dule: Peripheral swarm-dule holds the BLDC (Brushless DC) motors and propellers which are employed in the aerial mode. A pair of motors with differential drives along with a castor wheel are used for the movement in the ground mode, along with other necessary sensors, processors, and communication systems. Every peripheral swarm-dule has an onboard controller. This controller does not have any function in the aerial mode. However once the system is decoupled to ground mode from aerial mode, it controls the motion of the peripheral swarm-dules. A docking mechanism enables the peripheral swarm-dules to attach to the central swarm-dule. However, we do not provide design of docking mechanism here. Any of the docking mechanisms reported in the literature on modular robotics may be used. However, the design should take into consideration the load acting on the mechanism when the modular quadcopter is flying, and also ease of docking/undocking process. A conceptual design of the peripheral swarm-dule within the ROS environment is shown in Figure 3 (b).
The power for the BLDC motor is provided by the central module. This power gets detached in ground mode of operation. Thus, an additional power source is provided in the peripheral units, for ground mode operation. The configured model of the swarm-dular quadcopter within the ROS environment is shown in Figure 4.

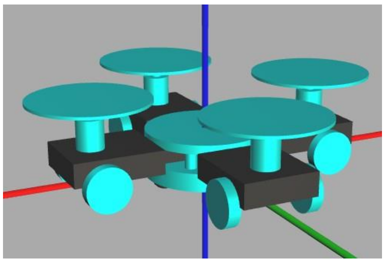

Fig. 4: A configured swarm-dular quadcopter within ROS environment

4. Modes of operation

Unlike a standard quadcopter which is only ca- pable of performing an aerial surveillance, the pro- posed swarm-dular quadcopter can function both as an aerial vehicle/robot and as several AGVs. Such a capability is very useful in several applications, such as search and rescue, surveillance, etc.

Individual mode

Individually each swarm-dule can operate as AGVs in the ground mode or on configuring into an individual quadcopter as UAV in aerial mode.
Ground Mode: Both the central swarm-dule and the peripheral swarm-dule have functionality of AGVs. Hence, each individual swarm-dule, central or peripheral, can operate in ground mode and perform functionality of a mobile robot/AGV.
Aerial Mode: Once a central swarm-dule docks with four peripheral swarm-dule, the configured quadcopter operates in the aerial mode as a UAV. In this mode, as noted earlier, the individual modules loose their functionality as ground vehicles.

Swarm mode

The swarm-dules can function as a swarm of robots. Following swarm modes can be realized.
Heterogeneous swarm of AGVs: Here the central and peripheral swarm-dules can function as members of a heterogeneous swarm of mobile robots/AGVs.
Homogeneous swarm of UAVs: Multiple configured swarm-dular quadcopters can operate as swarm of UAVs.
Heterogeneous swarm of UAVs and AGVs: A few swarm-dular quadcopters along with a group of heterogeneous AGVs formed by central and peripheral swarm-dules, can operate as a heterogeneous swarm. Such a configuration is very useful in many applications such as search and rescue.
Based on the application requirement, the swarm-dular concept can be applied to hexacopters, octa copterss and other multirotor. Based on the configuration of the multirotor, the number of available ground vehicles is n + 1 where n is the number of rotors in a multirotor.

5. Simulation results

The swarm-dular robot system has been simulated using Gazebo in the ROS Hydro version in Ubuntu 12.04 operating system. The robot models are described in Unified Robot Description Format (URDF). We have used Hector- quadrotor in ROS for simulating aerial mode of operation.
Central swarm-dule provides desired position and orientation to four peripheral swarm-dules to enable docking. Figure 5 shows path followed by the peripheral swarm-dules to the desired relative position and orientation and getting ready for docking. Here, the individual peripheral swarm-dules operate in individual ground mode. Once the peripheral swarm-dules get into respective docking position and orientation, the docking mechanisms will be activated. However, as mentioned earlier, we do not explicitly address the docking mechanism, instead, once the swarm-dules get into the docking position, they are considered docked.

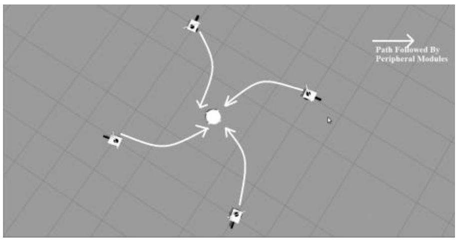

Fig. 5: Perpheral swarm-dules move toward the central swarm-dule for docking

Once the peripheral swarm-dules dock into the central swarm-dule, the flight control takes control and the swam-dular robot now operates in individual aerial mode. A simulation result of the aerial mode of operation is shown in Figure 6.

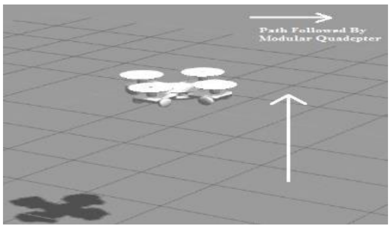

Fig. 6: Once docked, the swarm-dular quadcopter operates in aerial mode

Next, we provide the simulation result of the swarm behavior of the central and peripheral swam- dules. In fact, the motion of the peripheral modules to docking position too is a swarm behavior, where, the central swarm-dule acts as a leader. Figure 7 shows a consensus problem being solved by the four peripheral swarm-dules lead by the central swarm-dule after undocking. Note that the peripheral swarm-dules initially have heading direction corresponding to docking position, and then align in the direction of the central swarm-dule.

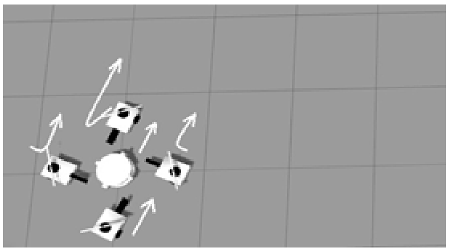

Fig. 7: Peripheral swarm-dules aligning their heading direction to that of the central swarm-dule after undocking, demonstrating a swarm behavior

Figure 8 shows another scenario where two con- figured quadcopters, four peripheral swarm-dules, and a central swarm-dule swarm-dular are functioning as a heterogeneous swarm. Individual swarm- dules are preparing for docking while other two swarm-dular quadcopters are functioning in aerial mode.

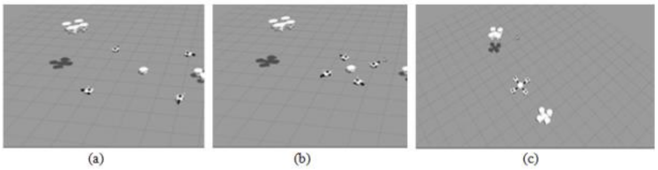

Fig. 8: Heterogeneous swarm of two swarm-dular quadcopters, four peripheral swarm-dules, and a central swarm-dule.

6. Conclusion and scope for the future work

In this paper we proposed the concept of swarm- dular robotics bringing swarm robotics and modular robotics together. We conceptualized a swarm- dular quadcopter, where a central swarm-dule combines with four peripheral swarm-dules, both of them capable of functioning as AGVs individually, to form a quadcopter. We discussed both swarm behavior and modular behavior of the proposed swarm-dular quadcopter. Finally the proposed concept is demonstrated with simulation experiments conducted within ROS environment, based on the conceptual design of the central and peripheral swarm-dules.

Detailed design and realization of a swarm-dular quadcopter is part of ongoing work. Also, we are working toward more realistic simulations, based on detailed design, and also experimentation with physical swarm-dules, once developed, in terms of various modes of operation and docking/undocking.

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