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Coaxial Modular Aerial System and the Reconfiguration Applications

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***Abstract*— This paper presents a coaxial modular aerial system (CMAS) formed by homogeneous modules driven by their center of mass. CMAS is designed to perform independent and cooperative flight with or without payload. Properties of the modularity concept allow the system to adapt to different situations and/or tasks by adding/removing modules to/from a configuration. The CMAS module is based on a coaxial motor and a two degree-of-freedom mechanism that transfers its center of mass from one side to another to make the module navigate around. The magnetic-based connector mechanism allows the module to be attached to other modules and to different metallic surfaces. A decentralized and asynchronous 3D path planning algorithm is implemented to avoid the trajectories of other modules/obstacles and ensures safe reconfiguration of the modules. Simulations within various environments show the applicability of the reconfiguration algorithm.**

I. INTRODUCTION

The modularity concept has been applied to different domains, for instance, within the cognitive sciences, biology, industry, as well as, within the robotics world [1], [2], [3], [4]. Generally speaking, a system can be characterized as modular to the extent that each of its components operates primarily according to its own. Modules within a system are tightly integrated but relatively independent from each other. Modules are able to either physically or virtually connect, interact and/or exchange resources by utilizing a standard interface or mechanism [5]. Over the years, there have been different approaches that addressed different problems among various domains, all within the modular robotics community. From conceptual systems, simulations, to physical implementations as a proof-of-concept. They all agreed that modular systems can bring versatility and robustness, as long as the systems are kept simple [6]. Some modular systems have been applied in different domains such as ground robots (e.g., for industrial applications, for search and rescue scenarios, for entertainment, etc.) [7], [8], space applications [9], [10], healthcare [11], among others. However, from a modularity point of view, there is one domain that has barely been explored, aerial robotics [12].

Nowadays, efficient surveying methods for geospatial data acquisition benefit from using data collected by a variety of autonomous systems, e.g., unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned underwater/surface vehicles (UUVs and USVs), etc. They can explore different scenarios utilizing a wide variety of sensors, whether in the air, on the ground, or in the water. These systems can perform different tasks and get close to specific locations, therefore increasing the quality of the sensors' readings. However, commercial off-the-shelf UAVs are limited by both payload capacity and battery life while flying. Typical UAVs are either designed to record aerial footage, or for recreational use. The capability of a standard UAV is limited by its task-oriented design [13]. Particularly, multi-rotor systems such as quadcopters, hexacopters and octocopters on the market possess pairs of propellers and maneuver by varying the thrust to each propeller [14], [15]. A malfunction on any of their components, such as a propeller, battery, etc., could cause significant delay or failure in any type of task or mission. Each of the mentioned systems has different benefits and disadvantages. A quadcopter is less expensive, small in size (compared to the rest), and great for carrying small objects (not strong enough to carry heavy payloads). The hexacopter brings better stability and can partially continue working even after losing a motor. It can also fly higher than a standard quadcopter and can carry heavier payloads. The octocopter is the strongest among them, it can fly at greater heights and carry heavier payloads. However, it is expensive, it requires constant battery recharge, and its size makes the system difficult to transport. Depending on the application and task, the multi-rotor system has to be designed according to specific needs either as a single task or for a potential collaborative task [16], [17], [18].

With respect to modular systems that can fly, there is one platform consisting of single-propeller modules that are able to dock with their peers, and fly in a coordinated fashion [19]. Single modules are not able to fly and navigate around. They must be connected to other modules to properly fly. Recently, there is another approach that uses quadcopters, as modules, each module surrounded by a light-weight square frame and four magnetic connectors for docking/undocking other modules [20]. This research work focuses on developing control strategies for the self-assembling of flying modules.

The coaxial modular aerial system (CMAS) presented in this work attempts to bring a solution to these challenges. It builds upon a conceptual introduction where a simulation analysis of its dynamics was performed [21]. CMAS is composed of homogeneous modules of a compact size that can work in a collaborative manner with the possibility to carry different payloads according to the needs. If one of the modules present a malfunction, this module can be easily substituted by another module and continue the task. A modular system could bring versatility, robustness, and scalability to different scenarios, since modules can be rearranged in different ways to form different configurations.

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II. COAXIAL MODULAR AERIAL SYSTEM

The main element of a modular system is the module itself. The conceptual idea of this system follows the idea of having homogeneous modules capable of executing typical tasks that are done by fixed-wing and multi-rotor systems, such as, taking-off, hovering, navigating, and carrying payloads. Due to the modularity nature, different modular configurations (MC) can be assembled for fast response to different tasks such as, in urban search and rescue operations, (e.g., safely and quickly scanning for threats inside buildings, delivering equipment, etc.), geospatial applications (e.g., deployment of sensor networks either for establishing/improving communication within a restricted area or for data gathering from ground, sea, and air), etc. A modular aerial system will be capable to adapt on-the-fly to different situations and needs.

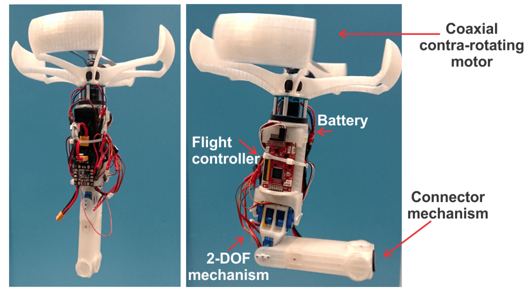
A. CMAS Module

The main element of CMAS, the module, is based on a coaxial contra-rotating motor (as the main source of propulsive power), a two degrees-of-freedom (DOF) mechanism or lower arm (as the mechanism that drives the module around), and a connector mechanism that allows the module to connect to other modules or objects, as shown in Fig. 1. The module is capable of navigating around by altering the position of its center of mass. This is accomplished by altering the lower arm, as shown in Fig. 2.

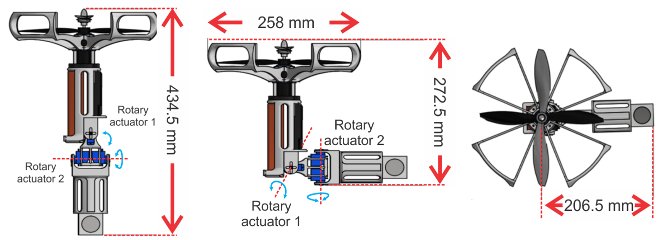
The prototype design features a Himax contra-rotating motor (CR28050) capable of 1.95Kg static thrust. The coaxial motor works with two brushless 20A electronic speed controllers to control RPMs and direction of rotation of the motors. The battery powering the system is a LiPo battery with a voltage of 11.1V, and a capacity of 5500 mAh. Two servomotors are used to control the lower arm of the module and a flight control module for general flight operations. Prototype has a weight of 0.83Kg, a payload capacity of 0.30Kg, an experimental static thrust of 1.43Kg, and a flight time of 7 minutes at full speed.

B. Navigation Principle

Similar to transverse weight movements in ships, the position of the center of mass of a CMAS module can be modified by adjusting the lower arm (2-DOF mechanism), as shown in Fig. 2(a). This adjustment causes the axis of the coaxial motor to tilt. As air flows around the module, pressure and shear stress distribution cause aerodynamic forces to act on the body in motion. These forces, lift (the strongest force acting on the module) and drag, act orthogonal when considering only the propellers. It can be observed in Fig. 2(b), the forces acting on the module when moving horizontally or while changing direction. Lift and thrust act in line with the flow of air through the propellers. The drag acts opposite the direction of movement, similar to friction. The resultant force, is decomposed into a horizontal (x-axis) and vertical (z-axis) component due to the inclination angle of the propellers' plane.

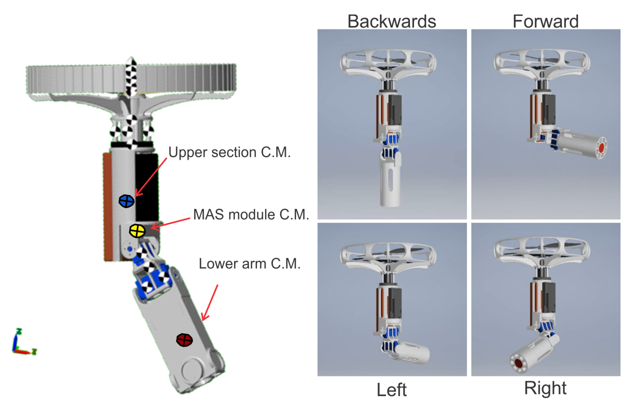


(a)



(b)

Fig. 1. (a) CMAS module. (b) Module dimensions (mm).



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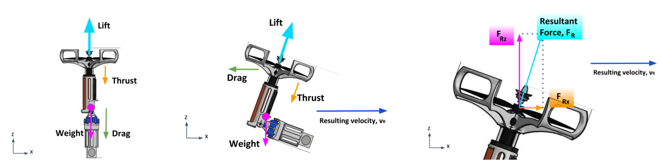


(b)

Fig. 2. (a) CMAS module center of mass (C.M.) position changes when lower arm C.M. is modified. This configuration is module's position of equilibrium. Propeller's plane rotates around Y and X axes to drive the module within different directions. (b) Forces acting on the CMAS module when moving around the environment.

III. RECONFIGURATION PLANNING FOR CONFIGURATIONS/APPLICATIONS

The CMAS's key feature is the modular characteristic. With a set of modules, it is possible to use the system for different applications such as package delivery, sensor deployment, data acquisition with a variety of sensors (regardless of size and weight), and for the creation of new modular configurations (MC) that enable the execution of different tasks. The main benefit of CMAS over traditional UAVs is that it is well suited for situations involving varying tasks/loads/sizes within the same mission, as shown in Fig. 3.

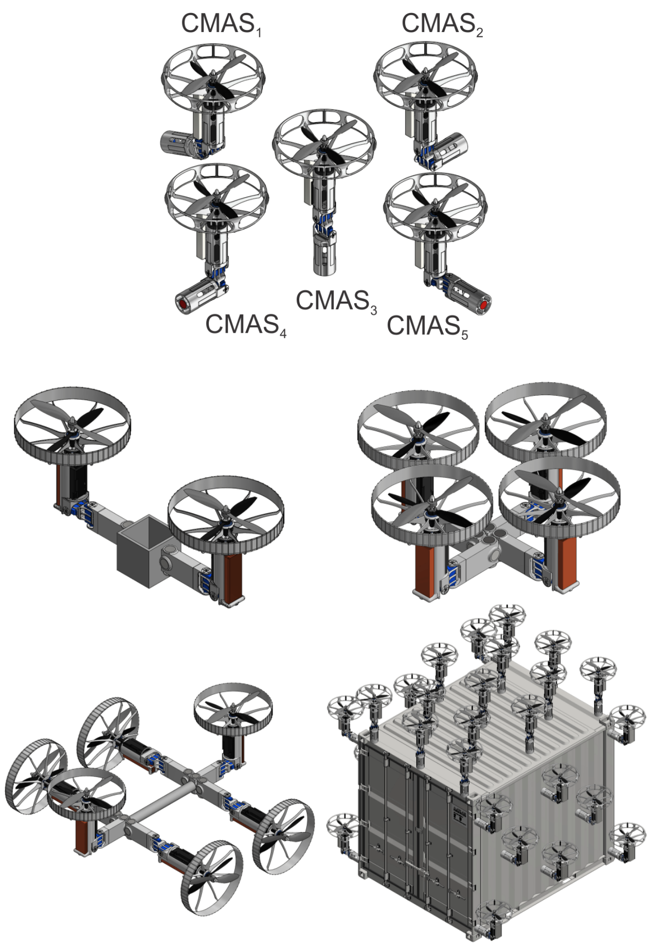
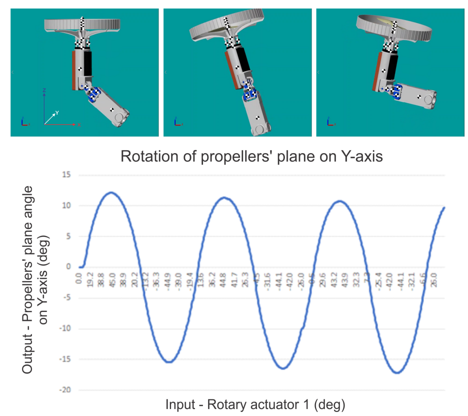


Fig. 3. CMAS configurations and applications.

Reconfiguration planning plays an important role in enabling modules to achieve the position in the corresponding configuration. Depending on the task, it may be required to assemble a two-modules configuration (2-MC), four-modules configuration (4-MC), six-module configuration (6-MC), etc. Each MC requires individual modules to approach corresponding goal positions to form the MC. Given the start and goal positions of the modules, planning an obstacle-free path will make the navigation and reconfiguration more safe and efficient. There are various path planning methods that can be adopted for path-planning such as artificial potential fields [22], A* algorithm [23], particle swarm optimization [24], ant colony optimization(ACO) algorithm [25], and variants of RRTs [26]. In this paper, we take inspiration from MADER [27]; a 3D decentralized and asynchronous path planer, that includes the committed trajectories of other modules as constraints in the optimization, performs a collision check-recheck scheme, and hence guarantees safety. In environments with static and dynamic obstacles, MADER is able to plan obstacle-free paths (from start to goal positions) for each of the modules. We have integrated MADER in order to achieve the path-planning of modules to create specific MC. In this application (Fig. 5), MADER considers the launchpad and the target configuration as obstacles, as they are rigid objects and should be avoided.



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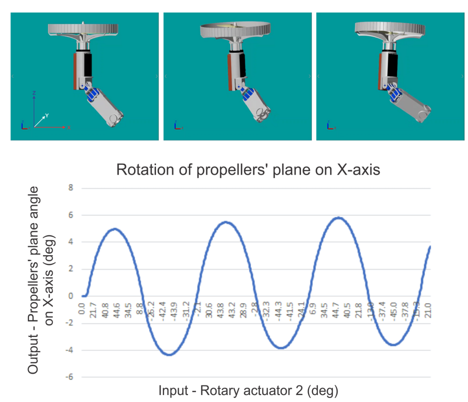

(b)

Fig. 4. (a) CMAS displacement when rotating first DOF of the lower arm. (b) CMAS displacement when rotating second DOF of the lower arm.

IV. SIMULATION ANALYSIS

The CMAS module was designed and simulated to validate its performance. Similarly, the creation of different MCs were simulated to test the path planning strategy.

A. *Movement Performance*

The CMAS module, particularly, the 2-DOF mechanism or lower arm has been simulated using Simscape Multibody along with Simulink to verify that the lower arm can drive the module around (shown in Fig. 4). We evaluated the change in position of the center of mass of the module and the rotation of the propeller's plane around X and Y axes. The input for this analysis was the actuation of the first DOF (rotary actuator 1) between a range of ± 45 °from an equilibrium position where the upper frame was aligned with the z-axis. Fig. 2(a) displays upper and lower parts of the module, alongside with the position of their corresponding center of mass. Similarly, the second DOF (rotary actuator 2) is tested to analyse system's rotation. By rotating it ± 45 °, the module was able to move in the left and right directions.

Simulation results in Fig.4(a) show that the propeller's plane angle on the Y-axis, caused by the actuation of rotary actuator 1, rotates within a range [-15 °, 13 °]. The positive angles indicate a counter-clockwise (CCW) rotation and a backward movement. Similarly, negative angles indicate a clockwise rotation (CW) and a forward movement. An increment of this rotation produces an increment of horizontal velocity. These two factors are proportional, but not equivalent due to an associated loss in altitude. simulation results in fig.4(b) show that the propeller's plane angle on the X-axis, caused by the actuation of rotary actuator 2, rotates within a range [-4 °,6 °]. The positive angles indicate a CCW rotation and a movement to the right. Similarly, the negative angles indicate a CW rotation and a movement to the left.

B. Reconfiguration Path Planning

We have tested the path planning strategy to assemble four MCs and defined four environments with increasing complexity to validate its performance.

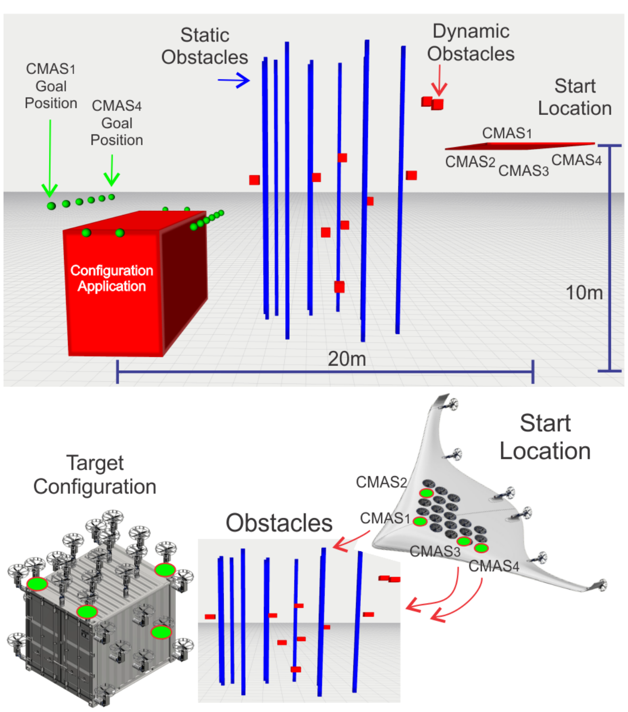

Fig. 5. Simulation environment of size 20m x 8m x 10m. It contains 10 randomly-deployed static obstacles of dimension 0.5m x 0.5m x 15m and 10 dynamic obstacles of dimension 0.5m x 0.5m x 0.5m.

As shown in the Fig. 5, we considered a volume of 20m x 8m x 10m as the simulation environment that contains 20 randomly deployed box-like shapes that resemble 10 static and dynamic obstacles each. The dimension of the static and dynamic obstacles are 0.5m x 0.5m x 15m and 0.5m x 0.5m x 0.5m, respectively. The position of the static obstacle is completely random but fixed during the span of a run, while the dynamic obstacle follows a trajectory given by the parametric equation of the trefoil knot. The modules' start and goal positions are set in a way to have a sufficient confrontation with the obstacles. In this work, we assume that before the configuration takes place, all the modules are attached to the bottom of a carrier in close proximity, as depicted in Fig. 5. The carrier is simulated as a red square shape at an altitude of 10m. Each module is assumed to be a point shape with 0.15m radius.

V. EXPERIMENTAL RESULTS

To validate the simulation results, the CMAS module was tested within two categories, i.e., real prototype and configuration path planning via simulation.

(a)

Input rotation angle servo motors	Output rotation angle Y-axis	MAS unit movement direction
-45°	12.10°	Backwards
-30°	8.28°	Backwards
-15°	4.08°	Backwards
0°	0°	Equilibrium
15°	-5.95°	Forward
30°	-10.90°	Forward
45°	-15.50°	Forward

(b)

Input rotation angle servo motors	Output rotation angle X-axis	MAS unit movement direction
-45°	4.96°	Left
-30°	3.30°	Left
-15°	1.52°	Left
0°	0°	Equilibrium
15°	-1.95°	Right
30°	-2.90°	Right
45°	-5.50°	Right

(c)

Fig. 6. (a) Experiments with the real CMAS module. (b) CMAS displacement when rotating first DOF of the lower arm. (c) CMAS displacement when rotating second DOF of the lower arm.

A. CMAS Prototype

The CMAS prototype is capable of taking-off and changing position by varying the center of mass. The position of the lower arm is controlled by a remote controller that actuates the two pair of servos in two degrees of freedom for navigation, as shown in Fig.6.

The arm of the CMAS module can be positioned perpendicularly to the vertical axis to allow a modular configuration with other similar units. The system offer the capability for the user to plan a flight using a friendly interface or manually control flight. Interface used is ArduPilot Mission Planner.

B. Configuration Path Planning

We mainly evaluated the success rate and the time taken by all the modules to achieve a configuration in various environments. The set of experiments has been performed in four environments: (1) without any obstacles, (2) static obstacles only, (3) dynamic obstacles only, and (4) static and dynamic obstacles, as shown in Fig. 7. Within each environment, we have tested configurations of two, four, six, and sixteen modules. Furthermore, each configuration is executed 10 times in each environment. For example, a two-modules configuration (2-MC) is tested 10 times in each of the four environments, resulting in a total of 40 runs for the 2-MC only.

The success rate and the time taken to achieve a configuration varies with the number of modules in the configuration and/or the type of environment. The more cluttered obstacles an environment has, the more chances to have collisions for the modules with each other and with the obstacles, and vice versa. For instance, in an obstacle-free environment, the success rate is 100% for up to sixteen module configurations but in an environment with static and dynamic obstacles, the success rate decreases from 100% to 50% from two to sixteen module configurations.

In the case of an obstacle-free environment, the only constraint for each module in the configuration is to avoid the trajectories of other modules, This makes them dependent on the initial position of the module. If the distance between the module is large, they will have less confrontation with other modules in the configuration, resulting high success rate and minimum time to achieve the configuration. In our experiments, for modules with a 0.15m radius dimension, the distance between the modules in a configuration is kept from 0.5m to 1m.

In an environment with static and dynamic obstacles, the module in a configuration has to plan a trajectory that avoids the obstacles and the other modules to reach the configuration position. Hence, for a configuration with more than six modules, the success rate and time taken to achieve a configuration, in this case, is relatively low and high, respectively. For instance, a configuration with two modules takes 6.22 seconds in an obstacle-free environment and 6.91 seconds in a static and dynamic obstacle environment to achieve a configuration, while a sixteen-module configuration takes 25.47 seconds in an obstacle-free and 52.72 seconds with static and dynamic obstacles environment, as shown in Fig. 8.

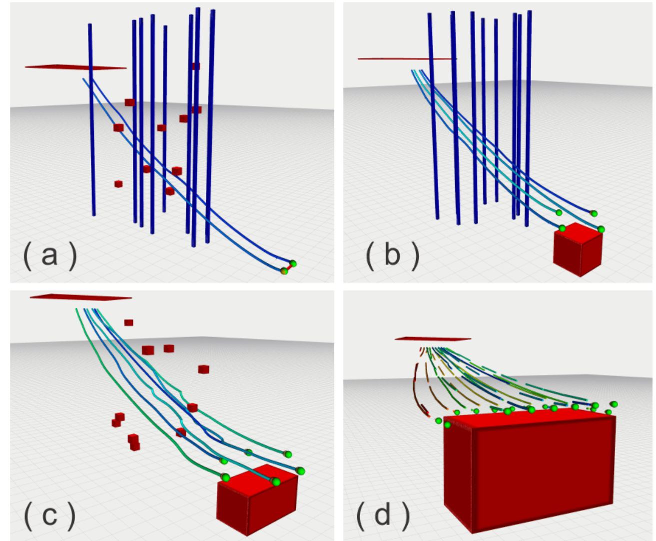

Fig. 7. (a) Results for Path-planning and configuration achievement with 2-MC in an environment containing 10 static obstacles and 10 dynamic obstacles. (b) 4-MC in an environment containing 10 static obstacles only. (c) 6-MC in an environment containing 10 dynamic obstacles only. (d) 16-MC in an obstacle-free environment.

In this work, we assume an experiment to be successful if all the modules involved in the configuration reach the configuration positions. If even a single module fails to reach the configuration, the experiment is considered a failure. For instance, in sixteen modules configuration in a dynamic obstacle environment, two runs out of the ten runs have failed because one module in each of the two runs failed to reach the configuration position, resulting in an overall success rate of 80%. We also calculated the Module Achieved Position in Configuration (MAPC). MAPC is the success rate of successful modules in all ten runs that have reached the configuration position. It can be observed in Table I, the success rate to achieve a 16-MC in a static environment is 40% but the MAPC, in this case, is 95.62%, which is the percentage of the total modules involved in the overall experiment that have reached the configuration position.

VI. CONCLUSION AND FUTURE WORK

In this work, a Coaxial Modular Aerial System (CMAS) was introduced, along with a simulation analysis of its performance. The dimensions of the module's frame permits to fit all electrical components, as well as, components necessary to add the modularity aspects into the system. The 2-DOF mechanism or lower arm permits the module to maneuver around the X-Y plane by changing its center of mass location, and when in combination with the coaxial motor, it allows the system to maneuver around the three axes. The passive connector mechanism (located as end-effector) brings multiple possibilities when trying to address different tasks by creating different configurations.

The dynamic simulations demonstrated the module's means of displacement by changing the location of its center of mass. By doing this, the module was able to produce movements in the forward, backward, left and right direction.

TABLE I

SUCCESS RATE AND TIME TAKEN TO ACHIEVE THE CONFIGURATIONS

Environment	Config	Config Achievement/10 Runs		Time-Taken Achieve Config/10 Runs			Std dev (Sec)
		SR-AC[1]	MAPC[2]	Mean (Sec)	Min (Sec)	Max (Sec)	
Without Obstacles	2-MC	100%	100%	6.22	6.18	6.40	0.07
	4-MC	100%	100%	8.03	7.73	8.49	0.20
	6-MC	100%	100%	8.18	7.94	8.92	0.33
	16-MC	100%	100%	25.47	23.70	30.14	1.86
Static Obstacles	2-MC	100%	100%	6.20	6.11	6.34	0.09
	4-MC	80%	95%	8.08	7.75	8.86	0.33
	6-MC	80%	96.66%	9.66	8.19	11.48	0.99
	16-MC	40%	95.62%	38.75	29.52	50.81	6.32
Dynamic Obstacles	2-MC	100%	100%	6.32	6.08	7.01	0.34
	4-MC	100%	100%	8.22	7.67	8.67	0.36
	6-MC	100%	100%	10.42	9.77	10.99	0.34
	16-MC	80%	98.75%	48.10	32.04	74.07	14.12
Static-Dynamic Obstacles	2-MC	100%	100%	6.91	6.14	9.52	1.23
	4-MC	80%	95%	8.49	7.76	9.94	0.63
	6-MC	90%	96.66%	11.40	10.31	12.87	0.75
	16-MC	50%	95%	52.72	38.75	93.20	15.96

[1] SR-AC: Success Rate to Achieve a Configuration [2] MAPC: Module Achieved Position Configuration

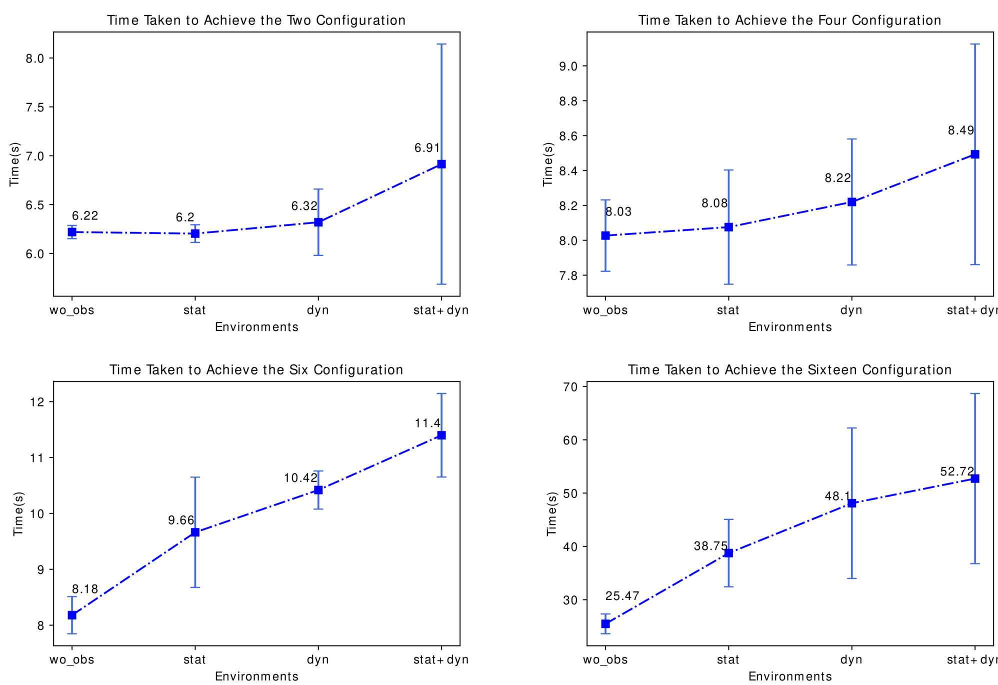

Fig. 8. Comparison of the time-taken by the modules to achieve the corresponding 2-MC, 4-MC, 6-MC and 16-MC.

It was also validated with the integration of a path planning technique for the assembly of modular configurations across different challenging environments. In an obstacle-free environment, the success rate to achieve a configuration does not vary with the number of modules for up to sixteen modules, as shown in Table I. Moreover, it can be observed from Fig. 8 that the mean time taken to achieve a complex configuration increases with the number of modules, and that the success rate decreases with the number of modules within an environment with obstacles. As future work, we plan to fabricate a set of CMAS modules to test performance of different configurations, explore various locomotion types by means of fuzzy controllers [28].

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