Hexapod Robots

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Contributor: Joana Coelho

The static stability of hexapods motivates their design for tasks in which stable locomotion is required, such as navigation across complex environments. This task is of high interest due to the possibility of replacing human beings in exploration, surveillance and rescue missions. For this application, the control system must adapt the actuation of the limbs according to their surroundings to ensure that the hexapod does not tumble during locomotion.

Keywords: mobile robots ; hexapods ; literature review

1. Introduction

Mobile ground robots have an important role in the replacement of human beings in tasks such as surveillance, demining, inspection, rescue and exploratory missions [1][2]. Their demand increases with the necessity of working in complex environments, where humans could be exposed to hazardous surroundings. Since these robots must walk across unforeseen scenarios, their success relies on their ability to autonomously adapt their motion according to the terrain topology and obstacles encountered without damaging their components. Therefore, the interest in the design of adaptable and fully autonomous devices has increased throughout the years.

Among the existent solutions, the legged solutions are adequate for walking across complex environments due to their discrete footholds and capability of generating trajectories in arbitrary directions [3][4]. From this type of robot, insect-inspired systems have been studied to navigate autonomously in complex environments because of their inherent static stability, which is the capacity for keeping the body stable and upright when only reaction forces are applied to the system [2][5]. Their over-actuated design allows the generation of different gait patterns, which can potentially increase their adaptability to the environment [6]. The control of these hexapods implies correct synchronization between the actuation of the limbs. The most traditional approaches follow predefined routines to generate and adapt locomotion. This type of control relies on the correct definition of the mathematical models of the robot to evaluate the influence of the surroundings in its internal state [7].

These systems have shown their versatility throughout the years, being capable of navigating through different terrain topologies and autonomously executing various chores. Nonetheless, recent advances in artificial intelligence (AI) potentially provide an increase in the autonomy of hexapods [8]. This technique can be implemented for multiple objectives, such as providing accurate perception of the environment, planning the motion of the robot or mimicking the adaptive behavior of animals. Another potential application of AI in these robots is for self-learning of how to walk considering their surroundings through a trial-and-error process.

2. Materials and Methods

The objective of this research is to evaluate how the design of hexapods is evolving to increase the adaptability of these systems in complex environments. To identify the recent advances in this area, an insight into the most commonly adopted methods for the control of six-legged robots is required. Through this analysis, it is possible to conclude the restrictions and advantages of each methodology and which ones may potentially provide better results for navigation across ever-changing environments. Consequently, this paper is based on a systematic literature review about the design and control of hexapod robots. Since there are no significant advances in the commercialization of hexapods for navigating in complex environments, this research considers only scientific publications related to the topic under discussion. Therefore, all the processed data was collected from the following data platforms: Science Direct, IEEE Xplore, Google Scholar, SpringerLink and Wiley. Among the keywords used during the systematic search, the terms “Hexapod”, “Six-legged robot”, “Navigation”, “Complex environment” and “Adaptive gait” were the most adopted ones. To understand the design of bio-inspired controllers, the keyword “Central Pattern Generator” was also searched. Moreover, to restrict the number of publications, only papers written in English were selected. The timespan selected for this study was 10 years, since the publications from the previous decade may not reflect the real stage of these research works. If in the established timespan there was more than one publication about a specific project, then only the most recent one was analyzed, except when the previous pieces of research contained useful information for this study. Moreover, if several papers proposed similar control methods and obtained similar results, then only the most recent one was not rejected. By the end of the systematic literature review, 57 papers were analyzed.

3. Control of Hexapods

The scientific publications obtained from the systematic literature review were categorized according to the methodology proposed for planning and controlling the locomotion of the designed hexapod (e.g., traditional controllers, bio-inspired architectures and Reinforcement Learning (RL)). For each category, the publications were presumed to provide an answer to the following questions: How was the hexapod tested? The control systems can be tested through simulations or experiments. However, testing the robot under real circumstances allows for concluding that the proposed system is reliable in uncontrolled conditions; What was the type of environment? Since the surroundings of the hexapod influence its locomotion, it is important to understand if there are robots already capable of autonomously navigating in extreme environments or if these systems have been mainly tested in controlled conditions. This research divides the type of environment into indoor with regular ground, indoor with irregular ground, which mainly consists of a household scenario with objects randomly displaced on the floor, stairs, depressions or ramps, and outdoor, which can contain the same obstacles seen in the previous case but also has different types of soil, with various friction coefficient values and more asperities; Does the hexapod generate an adaptive behavior? Despite some publications being mainly focused on the generation of stable locomotion, it is important to understand the limits of the adaptability in these robots; What type of sensors does the hexapod have? The selected sensors provide insight into the control system (e.g., if they rely mainly on proprioceptive or exteroceptive information to control and adjust the locomotion of the robot); Which computer vision algorithm was adopted? If the hexapod contains vision sensors to gather exteroceptive data, it also requires analyzing this information for the decision-making process.

The SSM has been widely used for the control of the stability of hexapods, mainly to evaluate if the torso is upright during the transition between the phases of the gait. In [9], the usage of the SSM aimed at ensuring that the robot generated a stable gait while walking across steps and ramps and that the machining tool remained centered with the body. Likewise, ref. [10] used the SSM to adjust the posture of a hexapod while walking across ramps with a maximum slope of 30 degrees. Along with aiming to reduce the energy consumption of the actuators of Noros-III, considering the desired motion of the object intended for manipulation, Ding and Yang [11] also used the SSM to evaluate the stability of the four-legged gait generated to carry the load. Zhao et al. [4] concerned themselves with the ability to overcome obstacles and calculated the SSM at each gait cycle to determine if the trajectory defined to surmount an object was stable. Additionally, Liu et al. [6] took advantage of the joint redundancy of hexapods and tested their ability to generate stable gaits when one of their legs malfunctioned, using the SSM to obtain the most stable configuration of the robot. Considering a different approach, ref. [12] adopted the Longitudinal Stability Margin (LSM), which is similar to the SSM, but it calculates the minimum distance considering the direction of motion. This method was implemented to generate stable locomotion when a hexapod walked across terrain with several forbidden places and was required to adjust its footholds to avoid them.

Although some of the previously described papers resorted to force torque measurements to detect the stance phase and changes in trajectory of the legs [13][14][15][16], the control of the deviation of the position of the feet or the angular position of the joints relied only on kinematic variables (e.g., position, velocity and acceleration). On the contrary, the dynamic formulation of the robot allows for obtaining an overview of its interaction with the environment through the analysis of the deviation of motion caused by the external forces and torques applied on the hexapod. **Table 1** summarizes all the pieces of research that contained this type of control. While Khudher, Powell and Abbod [17] used this formulation to generate a torque controller based on the desired acceleration of the feet for a hexapod meant to aid in humanitarian demining, ref. [18] focused on the generation of dynamic stable gaits. This piece of research presented the full dynamic model of a hexapod and tested the Dynamic Gait Stability Margin (DGSM), which evaluates the stability of a gait through the generated angular momentum and the edges of the SP. In this case, the hexapod was stable if the balance between the total angular momentum and the minimum angular momentum required to tumble the hexapod over an edge of the SP was positive.

Table 1. Publications regarding dynamic-based controllers (1: indoor regular ground; 2: indoor uneven ground and 3: outdoor).

Reference (Year)	Simulation/ Experiment	Environment	Adaptive Behavior	Sensors	Computer Vision Algorithm
[19] (2012)	Yes/No	1	-	-	-

Reference (Year)	Simulation/ Experiment	Environment	Adaptive Behavior	Sensors	Computer Vision Algorithm
[20] (2013)	Yes/Yes	1	Cargo transportation	-	-
[21] (2016)	Yes/Yes	2	-	Force sensors	-
[22] (2017)	No/Yes	2	Adjust to the terrain topology and carry objects	Force sensors, LiDAR, IMU and encoders	-
[17] (2017)	Yes/No	1	-	-	-
[23] (2018)	No/Yes	3	Adjust to the terrain topology	Stereo camera, encoders, current sensors and IMU	Visual inertial odometry
[18] (2019)	Yes/No	1	-	-	-
[24] (2019)	No/Yes	3	Walk across confined spaces	RGB-D sensor	Visual inertial odometry
[25] (2019)	No/Yes	3	Adjust to the terrain topology	-	-
[26] (2020)	Yes/Yes	3	Adjust to the terrain topology	Torque sensors and encoders	-
[27] (2020)	Yes/Yes	2	Wall walking	Force sensors, IMU and encoders	-

Aside from the generation of safe routes, the hexapod needs to know how to adapt its behavior. The method presented in [28] aimed at reducing the time required for the controller of a hexapod to plan its gait through an Artificial Neural Network (ANN) and Fuzzy Logic. The Fuzzy Logic was responsible for the determination of the correct actuation of the limbs in an unknown environment, while the ANN decided which was the most adequate locomotion pattern when the hexapod walked across an already known environment. The advantage of this method was that the robot did not need to evaluate the terrain because it knew from experience what was the most adequate gait. Considering a different issue, Tennakoon [29] included a Support Vector Machine to detect if the terrain collapsed with the contact forces of the hexapod when walking across brittle surfaces. Using this information, the robot adjusted the position of its CM and its footholds to avoid unsafe ground.

4. Conclusions

The static stability of hexapods motivates their design for tasks in complex environments, relying on the autonomy of their control systems to replace humans in hazardous environments. However, more than 85.00% of the studies did not refer to a final application for the designed hexapods, and only 5.26% mentioned the applicability of these robots for space missions, while 3.51% mentioned them for rescuing tasks. For the validation of results, 35.09% used experiments in real conditions, 31.58% resorted only to simulations and 33.33% considered both methods. Most pieces of research were still concerned with adapting stable symmetrical gaits for indoor environments with uneven ground (47.37%), while only 19.30% presented solutions for outdoor environments. Although 25.00% did not discuss the generation of any adaptive behavior, more than 35.00% aimed to generate locomotion adaptable to the terrain topology. By combining these results with the ones obtained for the type of environment, it can be concluded that most research still presents case studies for posture control and adaptation of the gait, using steps, depressions or ramps placed along a plane to verify the feasibility of their control systems. This means that a large number of pieces of research is in an intermediate stage to reach an adaptive control for outdoor surroundings. The adaptability of hexapods also has been tested for obstacle avoidance (17.54%), climbing abilities (10.53%), damage recovery (7.02%) and eccentrically transporting loads using one or two limbs (5.26%). These complex maneuvers emphasize the versatility of hexapods and their capacity to navigate and execute tasks in complex environments without human intervention.

Considering the time span of 10 years, the design of hexapods has gained more popularity since 2017, which also coincides with the rising interest in the implementation of model-free controllers. Regardless of that, the data gathered during the systematic literature review show that approximately 54.40% of the publications presented traditional controllers. Even though 55.56% of these systems used kinematic-based models to control the actuation of the limbs, the design of dynamic controllers aimed at obtaining an optimal energy consumption of the actuators by altering the stiffness of the limb according to the gait phase. Hence, 36.36% of these models were implemented in more complex environments, such as outdoor scenarios. While 33.33% of the papers used a bio-inspired approach to adapt the behavior of the legs, the rest implemented RL to improve the autonomy and learning abilities of the control architecture. Along with the recent advances in AI applied to robotics, the interest in these model-free controllers can be justified by the fact that they do not depend on complex mechanical models of the robots to actuate them, providing stable motor command in ever-changing environments, and they can improve the autonomy of hexapods. At the current stage of the state of the art, 42.11% of the bio-inspired systems were tested for indoor irregular terrain, which means that possibly in the next decade, there could be research showing good results for outdoor scenarios. However, for the usage of RL, approximately 57.00% of the papers only discussed the ability to learn to walk on indoor regular grounds, which means that the generation of adaptive locomotion remains an open question for this type of controller. Additionally, 42.86% of the results for this learning method were only based on simulations. Hence, due to the simplification of the environment and the model itself, some of these results may not be successfully replicated in real conditions. Another important remark is that although few papers discussed the combination of bio-inspired architectures with self-learning algorithms, its implementation not only may provide an optimal response to unexpected events but also accelerate the design of model-free controllers for exploration of unforeseen environments.

Due to the main interest in adjusting the actuation of a hexapod with the changes in the terrain, the most implemented sensors have the objective of detecting the contact forces between the feet and the ground, such as force torque sensors (26.32%), with some papers (almost 4.00%) studying the possibility of detecting these interactions using current sensors. Along with the implementation of an IMU or similar methods to detect changes of posture, the proprioceptive information reveals high importance for the control of hexapods. Moreover, almost 20.00% of the publications referred to the usage of vision sensors, but less than 10.00% discussed the implementation of computer vision algorithms. Thus, despite the recent advances in computer vision, there has not been a current implementation of these methods for gathering data from the surroundings.

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