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Abstract: Over the last five decades, legged robots, and especially six-legged walking robots, have aroused great interest among the robotic community. Legged robots provide a higher level of mobility through their kinematic structure over wheeled robots, because legged robots can walk over uneven terrains without non-holonomic constraint. Walking robots' locomotion mode is now a well-known problem that permits to address navigation tasks issues over uneven terrains. We present here a six-legged walking robot, called Hexabot, which is a 3D-printed, low-cost, small and light structure developed at LaBRI as an open source project. We explain our choice of Hexabot over other interesting robotic platforms such as PhantomX in our navigation setup, and provide ground-truth measurements of both Hexabot and PhantomX dynamics stability when walking on smooth, flat terrain. Thanks to its geometrical structure and dynamic behaviour, Hexabot showed the lowest orientation disruptions and a remarkably stable walk. Precisely, Hexabot's orientation and walking values are similar to those of desert ants, considering the scale factor. Finally, we describe visual cues needed in order to complete desert ant-like navigation tasks.

Keywords: Biomimetism, Biomimicry, Bionics, Biorobotics, Legged-robotics, Hexapod, Roll stability, Attitude stability

1. INTRODUCTION

Great advances have been made in hexapod walking robotics over the past decades, since first six-legged walking robots were built, performing animal-like but straight-line walking. From the end of the 60s to the begining the 90s, many hexapod walking machines were created. For instance, Gurfinkel et al. (1981) from the Russian Academy of Sciences of Moscow developed Masha, Bartholet (1983) from Odetics ITS Ing. developed Odex 1, and Koyachi et al. (1995) from the Mechanical Engineering Laboratory, AIST, MITI (Japan), developed the two hexapods Melmantis I and II. Most of them share the same caracteristics: large dimensions (generaly more than one meter), important weight (up to more than 150 kg) and low mobility and speed.

The next generation of walking hexapod robots includes major efforts of miniaturization. For instance, from the mid 80s, NASA's Graduate Student Researcher Program Fellowship Jet Propulsion Lab provided huge support to develop Genghis (Brooks (1989)) first and then Hannibal (Ferrell (1994)), two hexapod walking robots of small size (35 cm long) and weight (1kg). From the mid 90s, the FZI (Research Center for Information Technology, Germany) started the LAURON project (Legged AUtonomous RObot Neural Controlled), which led to several walking robots: LAURON I, II, III, IVc and V (see Roennau et al. (2010) and Roennau et al. (2014)). For instance, first version of LAURON weighs only 12 kg and is 50 cm long by 60 cm wide.

Although the first walking machines were built to provide solutions to issues met by traditional wheeled systems, hexapod robots tend to be designed to address the thematics of locomotion among insects: optimization and adaptability of gait generation, anatomic organization of the insects' legs, complex motion skills in uneven environments. Apart from the LAURON project, which got inspired by the Indian stick insect Carausius Morosus, we can mention RHex, a 6-DoF (degrees of freedom) walking robot designed at Boston Dynamics by Saranli et al. (2001), whose legs are curved and mounted on rotational articulations, taking inspiration from cockroach to consider the leg morphology and walking gait. Another example of robots' design based on cockroach is WHEGS, developed by Schroer et al. (2004) from Case Western Reserve University, which uses tri-spoke appendages that enable the robot to climb over small obstacles. Finally, Schneider et al. (2014) developed Hector (HExapod Cognitive auTonomously Operating Robot, from the University of Bielefield) which embodies one of the latest example

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of bio-inspiration among walking robots, including impressive biomimicry such as reflex behaviour to prevent any fault, and a decision-making system to provide insect-like walking behaviour, and intended for leg control, gait generation and body motion tasks.

Nowadays, in hexapod walking robots, gait generation and leg control during walking and running tasks are well-known problems, backed by five decades of research in this field of study. Consequently, we decided to develop a small walking, six-legged robot that will address challenging navigation tasks and benefit from the knowledge on the subject of gait control.

Homing tasks in desert ants have received great interest from entomologists. We now have plenty of information about what type of visual cues ants get and use while returning from feed source to their nest. To complete navigation tasks, desert ants rely on visual cues like optical flow, low resolution panoramic vision, and UV-light polarisation (see Collett et al. (2013) and Cheng and Freas (2015) for review). Raderschall et al. (2016) studied head roll stability affected by locomotion and how oscillations spoil navigation performances. In their study, they found that bull ants experience average head roll of 10° peak-to-peak. Similarly, Ardin et al. (2015) showed that *Cataglyphys velox*'s body pitch causes head pitch oscillations (up to 60° peak-to-peak when carrying food) that disrupts navigation performances. However, it seems that no mechanical compensation of pitch exists, and only a few compensation are made concerning head roll. One hypothesis Raderschall et al. (2016) proposed is that ants acquire visual informations when body oscillations reach their lowest level. Roll and pitch stabilities of the visual information appear to be one of the milestone in hexapod robot to navigate over an uneven terrain.

2. WHY HEXABOT ?

Perhaps the very first question should be: why a six-legged walking robot instead of a four-legged one? Hexapod walking robots have many advantages over quadruped ones: static gait (three to five legs are in contact with the ground at any moment), increased walking pace and more stability. Besides, hexapod robots can still walk with interesting performances if a damage occurs to one leg, as it was made possible in Cully et al. (2015).

Walking behaviour applied to hexapod robots is a well mastered issue. We can thus benefit from such knowledge to directly customize an already designed hexapod robot. Since customization step will increase the payload of the robot, it is important to have one with good payload capacity without disturbance over speed performance. Moreover, stability of the robot should not be affected by carrying a payload when walking. As we estimate global embedded-to-be electronics and sensors weight to be around 450 g, we rapidly came to hesitate between two hexapod robots.

2.1 The hexapod robots: Hexabot versus PhantomX

The first robot is PhantomX AX 18 (see fig. 1, top), designed by InterbotiX Labs (Trossen Robotics, Downers Grove, IL, USA). It has six legs, each using three degrees of freedom made using ultra fast DYNAMIXEL AX-18A series robot servos, providing an maximum speed of 80 cm/s when tested in optimal conditions: on a flat terrain, without sliding effect and with tripod gait. It should be noted that PhantomX maximum speed is presently the best performance. Another advantage of this robot is that it can carry heavy payloads (up to 2 kg, but with reduced speed).

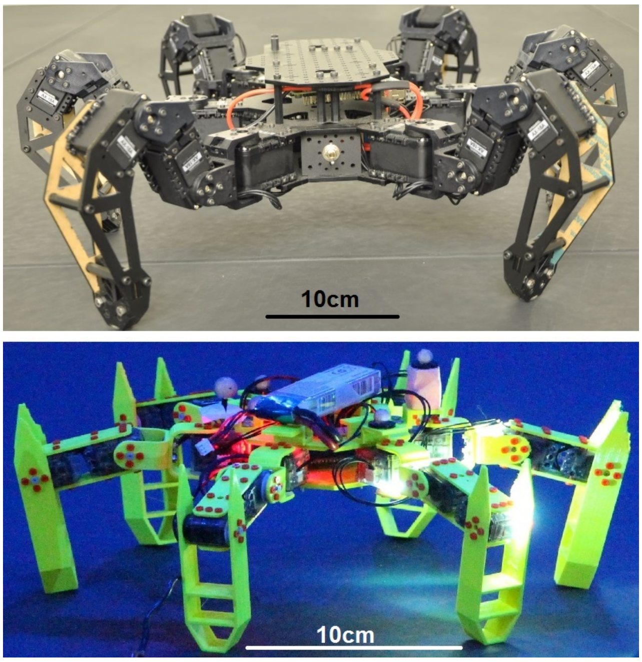

Fig. 1. The two hexapod robots PhantomX (top) from InterbotiX Labs, USA, and Hexabot (bottom) from LaBRI, France.

The second robot is Hexabot (see fig. 1, bottom), a fully 3D-printed, open source walking robot based on the Metabot[1] concept developed by Passault et al. (2016) at LaBRI Lab in Bordeaux, France. Since legs are printed with PLA filament (polylactic acid, a biodegradable thermoplastic aliphatic polyester derived from renewable resources), they require less effort to be moved during the transfert phase of walking movement. Indeed, each part of the legs are printed with low infill (20%) and 0.2 mm layer height. In those conditions, Hexabot reaches an optimum between maximum strength (the maximum stress the specimen can take before breaking) and overall weight. Another consequence of a reduced weight is that joints can be operated by less energy-demanding servos. Each leg has three degrees of freedom made with DYNAMIXEL XL-320 series robot servos, which are smaller and lighter than those used by PhantomX. The maximum speed of Hexabot is only of 35 cm/s in optimal conditions, but it will be enough to complete our navigation tasks. Finally, Hexabot can carry payloads up to 450 g without disturbing its walking behaviour (stability and speed).

2.2 Stability analysis

Geometric analysis provides interesting evidence that Hexabot would be a starting point for our experiments. The

[1] http://metabot.cc/

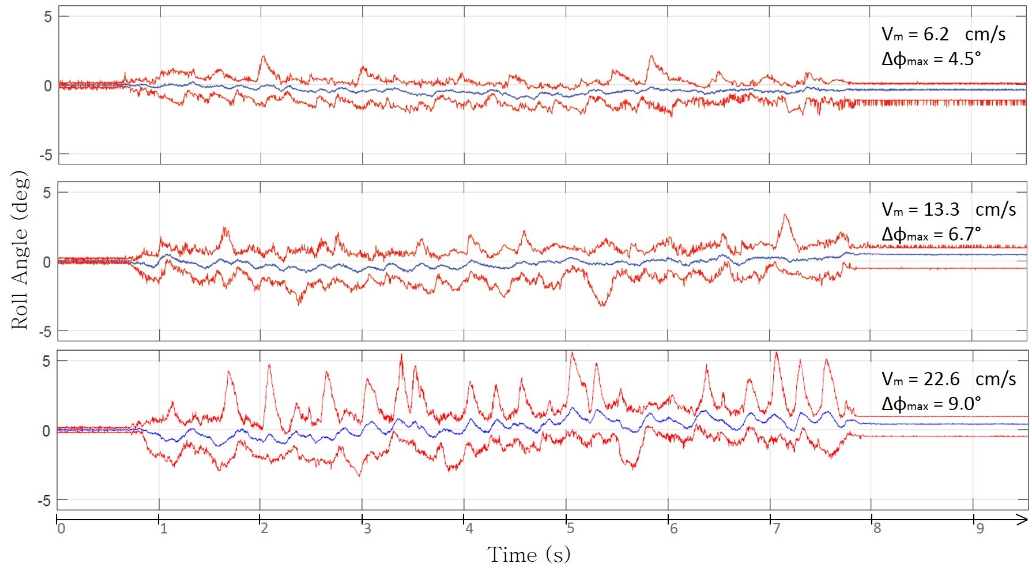

Fig. 2. The effect of locomotion over a flat terrain on Hexabot's roll stability. From top to bottom, graphs show roll behaviour when speed is 6.2 cm/s (resp. 13.3 cm/s and 22.6 cm/s). In this case, the maximum peak-to-peak roll disturbance is about 4.5° (resp. 6.7° and 9.0°). Blue curves correspond to average roll angle while red curves correspond to maximum and minimum roll angles over the ten iterations of the walking task.

geometric parameters of both robots are given in table 1. In particular, Chu and Pang (2002) demonstrated that the hexagonal model shows better stride length (in specific conditions), better turning ability and better stability margins than the rectangular model. Furthermore, the rectangular shape of PhantomX's body implies the use of crab walking or turn. On the contrary, the hexagonal shape of Hexabot provides a holonomic property that enhances direction changing aptitudes. In order to make the analogy with ants, table 1 includes Cataglyphis desert ants caracteristics. Considering the maximum body length, Hexabot is 10 times bigger than ants, and PhantomX is 20 times bigger. The ants' maximum speed is often in the range of 70 cm/s, which matches with PhantomX's speed performance, but walking speed is generally measured at 30 cm/s and coincides to Hexabot's speed regime.

		Hexabot	PhantomX	Ants
Body	Max length	115 mm	210 mm	10mm
Leg		215 mm	290 mm	8mm
Robot	Max length	525 mm	870 mm	
	Max height	145 mm	185 mm	
	Max speed	35 cm/s	80 cm/s	70 cm/s
	Overall weight	675 g	1975 g	10 mg

Table 1. Hexabot and PhantomX specifications. Overall weight does not include sensors, nor batteries. Equivalent values are given for desert ants Cataglyphis.

In order to analyze orientation disturbances caused by the walking behaviour of both Hexabot and PhantomX, we used the Flying Arena of the Mediterranean [2] (6m x 8m-x 6m-height) equipped with 17 motion-capture cameras (VICON) covering a uniquely reconfigurable flight space. Therefore, orientation angles were measured over time during straight-forward walking tasks of the robots.

Based on first observations, it seems PhantomX has *heavy* walk that involves lots of vibrations over its structure which would cause major visual artefacts and thus affect navigation performances. *A contrario*, Hexabot has a smoother walking behaviour due to its low weight.

The effect of walking tripod gait on the orientation of Hexabot was observed and figure 2 shows its roll stability over time at different speeds. For each speed, walking task was repeated ten times. We can notice that the faster the robot walks, the more important the roll disturbances. The wave shape is due to time intervals of tripod gait: the maximum of orientation disturbances occur during transfert phase of legs.

	Speed	Hexabot	PhantomX	Ants
Roll	50%	4.5°	7.4°	10°
	75%	6.7°	9.3°	
	100%	9.0°	11.3°	
Pitch	50%	4.4°	7.0°	60°
	75%	5.4°	9.7°	
	100%	9.9°	17.1°	
Yaw	50%	19.8°	9.7°	
	75%	19.8°	17.5°	
	100%	19.8°	28.4°	

Table 2. The effect of walking on orientation stability of both Hexabot and PhantomX, and the corresponding average value measured in ants. Angle values of roll, pitch and yaw are given in degrees and correspond to the peak-to-peak maximum amplitude observed during a straight-forward walking task, over 7 seconds. Speed values are percentages of maximum speed.

The entire results of orientation analysis are given in table 2. PhantomX shows greater roll and pitch turmoils than Hexabot, be the speed set to 50%, 75% or 100% of maximum speed. Consequently, Hexabot tends to be less prone to visual artefacts caused by locomotion. Interestingly, when walking at maximum speed, Hexabot shows the same roll displacement than ants. This observation is no longer true when considering pitch displacements. Indeed, there is a great similarity between Hexabot's roll

[2] http://flying-arena.eu/

and pitch displacements which can be explained by the strict symmetry of the hexagonal body of the robot, while ants' visual system is located on the head which is not directly connected to the legs. In other words, Hexabot's roll and pitch displacements are both caused by tripod gait locomotion, like ants' roll displacement, whereas ants' pitch displacement is greatly affected by carried food and roughness of terrain. Furthermore, it should be noted that yaw angles are considerably greater than roll or pitch angles. The reason is that both Hexabot and PhantomX use tripod gait, that is a gait where three legs (one on the left, and the two others on the right, forming a triangle shape, and vice-versa) are in contact with a ground at any moment.

3. CONCLUSION AND FUTURE WORK

Hexapods are well mastered and can be used to test biological theories about insect locomotion and navigation abilities. Hexapod robots with hexagonal shape show better performances in key tasks, especially in body orientation stability. We compared two walking robots, Hexabot and PhantomX, using our motion-capture system, and came to the conclusion that Hexabot, a 3D-printed, light and small robot, entirely met the requirements and will be a more reliable candidate for navigation tasks based on visual cues. Our robotic platform Hexabot has shown interesting walking skills but remains to be customized with sensors in order to complete navigation tasks such as foraging and homing, as desert ants like Cataglyphis and Melophorus do.

Hexabot will be equiped with sensors that will reproduce the same visual cues as desert ants in order to fulfill homing tasks in both indoor and outdoor conditions (Dupeyroux et al. (2017)). *Ceteris paribus* roll and pitch behaviours will afford the opportunity to adapt Hexabot to an ant-inspired walking robot, considering it provides the same range of roll displacements as due to its tripod gait locomotion.

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