Towards the design of a leg-wheel walking hexapod

Franco Tedeschi, Giuseppe Carbone
LARM, University of Cassino and Southern Latium
Via Di Biasio 43, 03043 Cassino (FR), Italy
franco.tedeschi@unicas.it, carbone@unicas.it

Abstract— **Hexapod walking robots have been widely addressed in literature. Their design requires to manage a very large number of design variables and design solutions. Thus, this paper proposes a procedure in order to systematically design a hexapod walking robot. A design case of study is described in order to show the effectiveness and feasibility of the proposed procedure. As results the design concept and mechanical configuration of a novel hybrid leg-wheel hexapod walking robot is presented. The proposed robot is composed of six legs having a modular anthropomorphic architecture with omni-wheels as feet at its extremity**.

Keywords— Leg-wheel walking hexapod, design procedure, preliminary design.

I. INTRODUCTION

Walking hexapod robots are programmable robots with six legs that are attached to the robot body. The legs are controlled with a degree of autonomy so that the robot can move within its environments, to perform intended tasks [1].

Legged robots possess clear advantages over wheeled robots like obstacle climbing capability, omnidirectional motion, variable geometry, good stability, access to uneven terrain, fault tolerant locomotion. Despite the above mentioned aspects, many challenges remain before hexapod walking robots can foresee a widespread use. Some of their current disadvantages include relatively low energy efficiency and low speed [2]. Other key factors that restricted a pervasive application of hexapod are high complexity and costs. In fact hexapod walking robots are usually expensive machines, consisting of many actuators, sensors, transmissions and supporting hardware.

A very reach literature can be found on hexapod walking robots, while each hexapod robot design is almost unique. For example, some ones are equipped with biologically inspired legs. This type of walking machines can be slow and more difficult to design and operate, on the other hand it can overcome obstacles that are comparable with the size of its legs [3]. There is also a further type of hexapod robots that is called "hybrid" since it has legs and wheels at the same time. This type of walking machines may range from wheeled devices to true walking machines with a set of legs to overcome particularly difficult obstacles, or wheels to enhance the speed when moving on flat terrain.

This paper focused on a preliminary design procedure in order to systematically approach the design of hexapod walking robot and identifying the most convenient design characteristics. A design concept of a hybrid leg-wheel hexapod walking robot is presented in order to show the effectiveness and feasibility of the proposed procedure.

II. THE ATTACHED PROBLEM

A very wide range of possibilities exist to design a hexapod. Some milestones in the early design solutions have been for example Masha, OSU Hexapod, Odex I, Aquarobot, ASV, Genghis and Ambler. Remarkable hexapod robots in recent design solutions have been for example, Hamlet, Boadicea, Rhex, Athlete, Lemur, Comet, Lauron, Rise and a series of bio inspired hexapods of Case Western Reserve University. The evolution of hexapod robots design was outlined in [4]; an overview of the state of art of hexapod robot was given also in [5]. However, each prototype shows specific design solutions and its design can be considered unique.

Considering the wide literature on the topic designers must take several decisions which influence the operation and technical features of a hexapod robot. Most important engineering requirements can be outlined as:

- body architecture;
- legs type setting;
- actuators and drive mechanisms.

In order to systematize the complex design process of a walking hexapod robot in this paper we propose a two steps design procedure. At first stage we propose a preliminary design in order to identify the key features and design requirements of the robot. Examples of key features in hexapod walking robots design can be walking speed, cost, load carrying capacity, autonomy, climbing obstacle capability, walking gait. A preliminary design is often a trade-off solution between design requirements and key features, but in literature it is lacking a systematic design procedure for hexapod robot as referring to specific functional requirements. On this matter some authors propose a Quality Function Deployment [6] in order to define the relationship between the design configuration and the robot capabilities or requirements. In this paper a simplified approach is proposed to relate and prioritize key features through numerical ranking as a tool for identifying a preliminary design solution. Then, design refinements are outlined by referring to the engineering requirements that have been identified at the previous stage.

III. DESIGN PROCEDURE

The proposed design procedure has been described in Fig. 1. Two main stages have been addressed: preliminary architecture

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design and design refinements. As a first step, the key features will be identified and then ranked by their importance to the project. Table I gives the proposed ranking criteria. Rankings values are recorded in the Importance Rating column of Table III. A different choice of weights can be adopted for Table 1. However, the assigned values define a priority factor. Thus, the key issue is to define a series of increasing values according to the importance of a key feature for the project. The use of a linear scale is a recommended choice for Table 1. Table II gives the criteria used to evaluate the importance of an engineering solution in fulfilling key features. Instead, the weights in Table II define a correlation factor. Thus, it is important to adopt a series of increasing values according to the fulfilling of a key feature. The use of a linear scale is not recommended in this case in order to emphasize the significance of fully fulfilled engineering requirements.

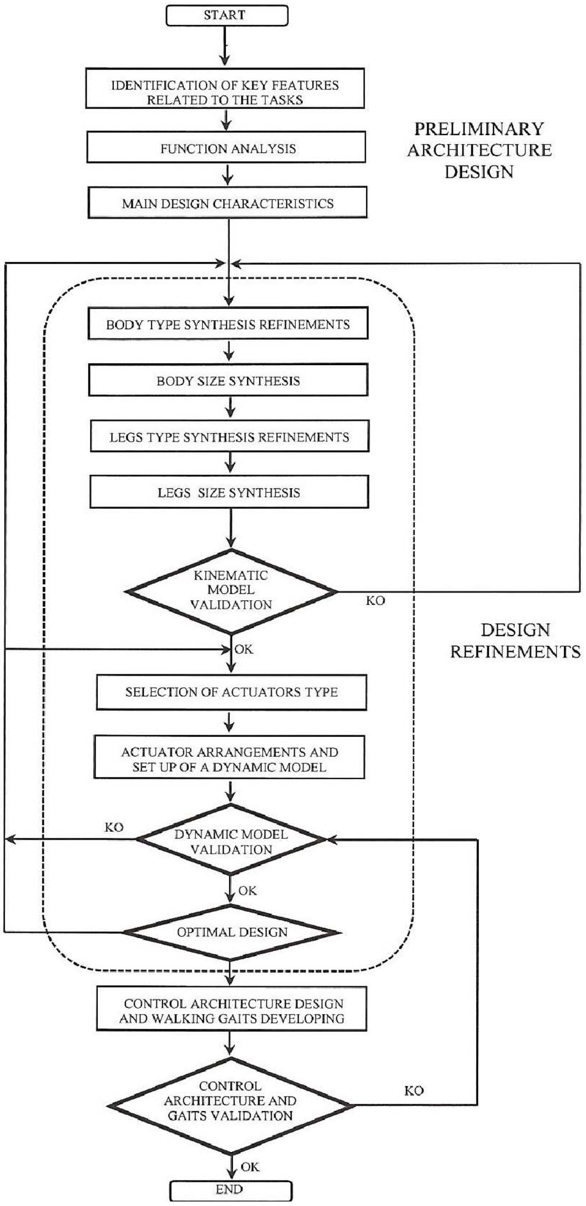


Fig. 1 Flow chart of the proposed design procedure

Table I: Ranking criteria of key features

Importance of key features	**Value**
Not important to project success	1
Somewhat important to project success	2
Fairly important to project success	3
Very important to project success	4
Critical to project: design driver	5

Table II: Correlation matrix values

Engineering solution satisfies the requirement:	**Value**
By itself	9
In conjunction with one or two design input	3
In conjunction with many other design input	1
Does not satisfy the requirements	0

Table III: Relationship matrix

Design requirements (How) / **Key Features** (What)		Importance rating R	K_1	K_2	K_3	K_4	K_j
			Body type	Legs Architecture	Actuators	Power Supply	....
			1	2	3	4	j
Walking speed	1						
Obstacle avoidance	2						
Load carrying capacity	3						
Operation	4						
Walking gaits	5						
Cost	6						
....	i						
$Y_j = \sum_{i=1}^{n} K_{ji} \cdot R_i$			Y_1	Y_2	Y_3	Y_4	Y_j

Table III relationship matrix will be completed by filling the key features-design requirements intersection according to Table II criteria. Then, the rankings are multiplied by the relationship value and totaled on each column of the matrix. The bottom of the column Y_j is the importance rating of the K_j engineering requirements. The result is a priority list of design requirements which can be used as a starting point in the choice of the hexapod architecture. This tool will help to focus the process development on the issues that are critical to the hexapod design. In order to allow the filling of the relationship matrix in the following we summarize some typical design issues that are related to the design of hexapod walking robots.

a) Robots shape

There are two basic architectures of hexapod robots: rectangular and hexagonal. The first one has six legs distributed symmetrically along two sides, each side having three legs. The second one has legs distributed axi-symmetrically around the body. Bilateral symmetry may be better suited than radial symmetry to move along a straight line but requires a special gait for the turning action. Hexagonal hexapod robots demonstrate better performances than rectangular robots for some aspects [7]. As example hexagonal robots can have many kind of gaits and can easily change direction.

b) Kinematics architecture

Fig. 2a shows a scheme of feasible hexapod legs types according to [8]. Legs topology can be bio inspired or non-zoomorphic. Non zoomorphic legs can be hybrids (leg-wheel), telescopes or whegs. Bio inspired leg configuration is motivated primarily on animal gaits, such as reptiles, mammals or arachnid. In the Reptilian type the legs are placed on both ends of the body and knees to the side of the base. Mammals have the body above the legs, they require lower power consumption to support the body, but need more stability than other types of animals [9-10]. In Aracnid configuration, legs extremities are situated on both sides, sticking the knees at the top of the robot's body. The orientation of the legs respect to the body of the hexapod robot can be frontal, sagittal or circular (Fig. 2b). In the frontal configuration the directions are perpendicular to the advancement of the legs position, unlike the sagittal, which moves parallel to the robot legs. In the circular arrangement the legs are positioned radially to the body allowing the mechanism to move in any direction [10]. In the mammalian configuration the legs can move the knees in different positions, such as shown in Fig. 2c).

c) Actuators

Many kinds of actuators can be employed by operating hexapod walking robots. Electric rotating motors are relatively cheap, easy to control and there are suitable technologies to storage the energy. Linear motors are able to generate considerable forces at very considerable speeds; however they do not appear to have been utilized in many hexapods yet, since they have a limited movable range to weight ratio.

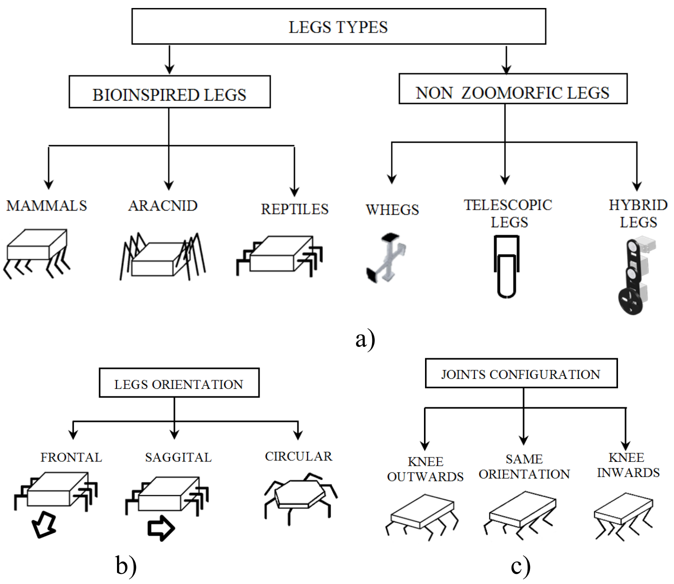


Fig. 2 Leg architectures: a) leg types b) leg orientation c) joints configuration.

Pneumatics actuators have low stiffness, inaccurate response, low power to weight ratio. Pneumatics actuators or air muscle, are able to offer a fast response time but they need of an on-board air supply as bottles or compressors that are heavy pieces of equipment. Hydraulics actuators have high power/weight ratio; they are able to supply very high force, but suffer from the serious drawback of having to carry a heavy engine to drive a pump. They are generally unsuitable for small sized hexapod robots.

Unconventional actuators for micro hexapod robots can be also materials that can change shape through the direct application of electricity or a chemical agent as Ionic polymer-metal composites, Shape Memory Alloy or Polyacrylonitrile.

d) Drive mechanism and actuator arrangements

Typically actuators arrangements are developed in order to obtain maximum leg workspace with a suitable kinematic architecture. Several types of geometrical arrangements such as in Fig. 3a), are recurrent in literature. The design consists of links connected through knee joints. The walking motion is accomplished by controlling the angle of the links to position the feet. There are a number of different ways in which the joints can be actuated such as referred in [11]. Options include mounting the motor at the joint itself or using a pulley-belt (Fig. 3b), or using a lead screw (Fig. 3c) to set the angle of the knee using an actuator mounted near the base of the leg [12]. Each design solution shows specific advantages and drawbacks. For example the lead screw solution avoids the need of a brake and reduces the inertial effects on the leg but requires more powerful motors at hip joints.

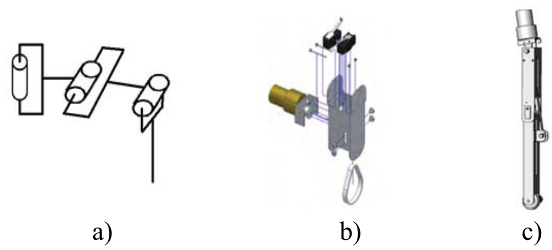


Fig. 3 Actuators arrangements: a) usual arrangements b) detail of pulley belt arrangements c) lead screw leg.

e) Gait planning

A gait is as a sequence of leg motions that are coordinated with a sequence of body motions for moving the overall body of the robot in the desired direction and orientation from one place to another [13]. A gait is called periodic when similar states of the same leg occur at the same interval for all legs during successive strokes. Periodic gaits such as tripod, or wave gait are suitable for smooth terrain. Periodic gaits require synchronization between the expected and actual times that legs make contact with the ground. Over uneven ground the time of footfall becomes unpredictable, breaking the defined leg phasing and compromising stability. The free gaits are much more effective on rough terrain with obstacles. The free gait is when each leg can move on a free chosen interval and own stroke algorithm. The difficulty with this approach is the computational complexity.

IV. A DESIGN CASE OF STUDY

This section will address the design of a hexapod walking robot by considering previous experiences at LARM. In particular the proposed robot is intended for tasks such as the inspection and operation in archeological sites, as reported in [14]. Based on the selected application, key features requirements can be summarized as follows:

- low-cost both in design and operation (< 1000 Euros);
- user-friendly operation, also for non-expert users;
- wireless operation in environments that cannot be reached or unsafe by human operators;
- capability to negotiate obstacles:
  a) a crest, with maximum width W=100, height H=60mm;
  c) a ditch, with maximum width W=100 mm;
  a) a step, with maximum height H = 60mm;
- able to carrying surveying devices;
-operating speed on regular terrain must be > 0.1 m/s;
-operating speed on uneven terrain must be > 0.05 m/s.

IV.I Preliminary architecture design

According to the above referenced criteria, Table IV shown a matrix related to a preliminary design. As a first step, the key features are ranked by their importance to the project, according Table I. It is worth to note that each key feature has been detailed in several aspects. As example, walking speed has been described in terms of performances on regular terrain and uneven terrain; the cost has been split in two factors: total budget and use of commercial components. Regarding the walking gaits, tripod and wave strategies have been considered. Also obstacle avoidance and operation requirements have been detailed in several aspects. Thus, key features rankings are recorded in the Rating of importance column of Table IV. Similarly, each engineering requirement has been decomposed in several items. As example body type item reports two solutions: firs one is rectangular shape, and second one is hexagonal shape. Leg types issue has been detailed in three items: configuration, orientation and knee. Leg configuration items have been detailed in mammals, reptile, spider and hybrid. Leg orientation can be detailed in sagittal, frontal, circular solution; knee orientation can be detailed in three categories: outwards, same orientation and inwards.

After the engineering requirements have been identified, the relationship matrix, will be completed according to Table II criteria and the above mentioned design issues. Thus, in the relationship matrix, the rankings will be multiplied by the relationship value and total is given as bottom of each column of the matrix. The value at the bottom of the column is giving the importance rating of the considered design requirements. These evaluations must be confirmed with simulation and trade-off studies, however only the highest ranked items are subject to design refinements; this will significantly reduce the required design time efforts. Final score in Table IV shows that the highest engineering requirements (values in bold) are rectangular body shape, hybrid legs, frontal orientation, same orientation knee, electrical actuators. According to this results, has been selected the preliminary hexapod robot architecture.

IV.II Outline of the design refinements

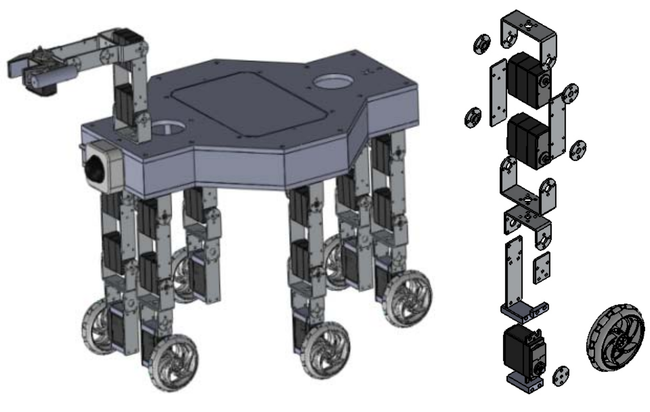
Design refinements have been carried out according to the second stage of Fig. 1. SolidWorks environment has been used due to its convenient features in structure analysis and in the operation study of multi-body systems in order to check the feasibility of a real prototype. Simulations have consisted in investigating basic robot performances in a virtual environment in order to check the design feasibility before prototyping. Components manufacturing will be carried out by using a CNC milling machine.

- Body type and size synthesis

Rectangular shape has been adopted according to the result of first stage design. The overall robot configuration is presented in Fig. 4a). This walking machine can fit into a cube of 0.4m x 0.3m x 0.2m. The robot body structure is composed of two main plates made of Delrin that are connected with screws and nuts. The main body can carry on-board a control card and battery. The overall robot weight is about 30N.

- Kinematics architecture

Legs Kinematics consists of two links connected through a knee joint. This assembly solution has been designed as based on previous experiences reported in [15]. Each of the legs has 3 DoFs: two of them have a movement that has a range between -90° and 90° that allows the robot to overpass obstacles and to walk without moving the wheels. The third motor allows to move the wheels in a full range rotation. An exploded view of the leg is shown in Fig. 4b). The low cost design of the legs has been obtained by using a kinematic solution with few components made in aluminum and by selecting commercial parts. The leg measures 160mm in length, 45mm in width and 20mm in depth. Total weight is about 2.5 N. The diameter of omni-wheels is 60mm. Omni-wheels are wheels with small discs around the circumference which are perpendicular to the rolling direction. The effect is that the wheel can roll, but can also slide laterally. The purpose of these wheels is to have the ability to steering the robots in wheeled operation via differential motion between omni-wheels on the left and right legs. The proposed solution has been adopted in order to improve the wheeled operation features developed in [16] by using traditional wheel: in this case a coordination of legs-wheels was needed in order to allow the robot steering.



a) b)

Fig. 4 a) Overall hexapod design b) exploded view of one leg

Table IV Preliminary matrix design

Engineering requirements design (How) / Key Features (What) i, j		Rating of importance R	Body Type		Legs type synthesis										Actuators		
					Configuration				Orientation			Knee					
			Rectangular shape	Hexagonal shape	Mammalian legs	Reptile legs	Spider legs	Hybrid legs	Sagittal	Frontal	Circular	Outwhards	Same orientation	Inwards	Electrical	Pneumatic	Hydraulics
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Walking speed																	
Regular terrain >0.1 m/s	1	5	3	3	1	1	1	9	3	9	3	3	3	3	9	3	3
Uneven terrain >0.05 m/s	2	3	3	3	3	3	3	3	3	9	3	3	3	3	9	3	3
Low Cost																	
Cost Under 1000 Euro	3	5	3	3	3	3	3	3	1	1	1	1	1	1	9	1	1
Use of commercial components	4	4	3	1	9	9	9	9	3	3	3	3	3	3	9	3	1
Obstacle avoidance																	
Step $H_{max} \geq 60$ mm	5	4	3	3	9	3	3	9	1	3	3	3	9	3	3	3	3
Crest $H_{max} \geq 60$ mm $W \geq 100$ mm	6	4	3	3	9	3	3	9	1	3	3	3	9	3	3	3	3
Ditch $W_{max} \geq 100$ mm	7	4	3	3	9	3	3	9	1	3	3	3	9	3	3	3	3
Operation																	
Wireless	8	5	1	1	1	1	1	1	1	1	1	1	1	1	9	3	3
Omnidirectional steering	9	4	3	3	1	3	3	9	3	3	9	3	3	3	3	3	3
Autonomy ≥ 1 hour	10	5	1	1	1	1	1	1	1	1	1	1	1	1	9	3	3
Walking gait																	
Tripod gait	11	3	9	9	3	3	3	9	3	3	3	3	3	3	3	3	3
Wave gait	12	3	9	3	3	3	3	3	9	3	3	9	3	3	3	3	3
Ground clearance ≥ 15 cm	13	3	9	3	9	3	1	3	1	1	1	1	1	1	1	1	1
Load carrying capacity ≥ 0.5 kg	14	5	3	3	3	3	3	3	3	3	3	3	3	3	9	9	9
$Y_j = \sum_{i=1}^{n} K_{ij} \cdot R_i$ Total Ranking			**205**	161	247	165	159	**319**	129	**183**	159	153	**207**	135	**357**	200	192

- Actuators type

It is necessary to install small and light type of electric motors for the joint actuator because of restriction of space and mobility. Commercial servomotors are suitable for controlling joints knee robot as they are small, light, and they have low cost. The adopted actuator can be a digital servo model DS RDS3115MG. Max torque is 1.47 Nm at 6V. Weight is 0.06kg. The adopted continuous rotation servo can be the RC servo model DS AS3103PG. Max torque is 0.39 Nm at 6V. Weight is 0.04kg. Dynamic model validation has been carried out such as outlined in [16].

-Walking Gait

Solidworks environments has been used for periodic gaits simulation such as for example, wave and tripod gaits. Wave gait will be adopted by the hexapod when it will move slowly. In the wave gait, all legs on one side are moved forward in succession, starting with the rear-most leg. This is then repeated on the other side. Since only one leg is ever lifted at a time, with the other five being down, the hexapod is always in a highly-stable posture.

Tripod gait is a gait where the front and back legs on one side lift in time with the contralateral middle leg, forming alternating tripods. This is a gait suitable for high speed walking over relatively flat ground.

- Control Architecture

A low cost control architecture has been developed by using a commercial control card Arduino Mega 2560, referring to previous experience at LARM [17]. The remote interface has been achieved by means the Arduino Wi-Fi shield such as outlined in [18]. The high level remote control will be developed in a Java environment: it allows task planning between a Wi-Fi network using a PC. A Li-Po battery 7.4V-5000 mAh, has been selected as suitable power supply. The overall weight of the battery is 0.35kg. Commercial DC-DC switching converters allow to adapt the output voltage of LI-PO battery to the voltage input of servomotors and control card.

V. PRELIMINARY PERFORMANCE EVALUATION

Preliminary performance indices of the proposed design have been estimated, such as example, robot's speed, obstacle climbing capability and energy performance.

The robots speed in a tripod gait can be estimated by using the definition in [19]:

$$V_T = Ls/t_T \tag{1}$$

where Ls is a step size, and t_T is the transfer phase,

$$t_T = (1-\beta)T \tag{2}$$

in which β is a duty factor and T is a cycle time.

The minimum duty factor of a six-legged robot is β = 0.5. For the proposed hexapod, the values are: Ls = 0.07m, and T= 2s thus, substituting in (2) we obtain:

$$t_T = (1-\beta)T = (1-0.5)2 = 1s \tag{3}$$

then, a maximum speed V_T can be computed by using (1) as equal to 0.07m/s. In wheeled mode a maximum speed can be estimated by multiplying the maximum motor speed by the perimeter of the wheel as V_w =0.17 m/s. The obtained result does not take in to account the hexapod mass, friction and rolling resistance. Climbing obstacle capability is 70mm, about 40% of robot leg. The result has been obtained through Solidworks simulation. In order to measure energy efficiency we use the Specific Resistance as proposed in [20]:

$$\varepsilon = \frac{P}{\mathrm{mgv}} \tag{4}$$

that can be referred to the robot's weight (mg), and its average power consumption P, at a particular speed, v. Referring to previous experiences at LARM for a similar application [17] medium value of P can be estimated as about 40W on uneven terrains and 15W on regular terrains. Considering the robot overall weight of 30N, the specific resistance is equal to 19.04 on uneven terrain, and 2.94 on regular terrains.

As a comparison with other hexapod robot characteristic such as in [21] the proposed hexapod exhibits good performance indices. Robot autonomy can be estimated as greater than one hour by considering that the battery energy is about 37Wh and a medium value of the required power is 27.5W. Considering the cost of the selected servomotors, control card, wi-fi shield and the other components, the overall cost of the robot will be about 600 Euros; thus a low cost feature has been obtained.

CONCLUSION

A novel procedure has been outlined in order to systematically approach the design of a six legs walking robots. The proposed procedure focused on a preliminary design architecture in order to systematically approach the design of hexapod robot and identifying the most convenient design characteristics. The proposed design procedure takes into account the key features such as walking gait, cost, load carrying capacity, autonomy, climbing obstacle capability. The result of a procedure is a priority list of design requirements which can be used as a starting point in the choice of the hexapod architecture. This tool will help to focus the process development on the issues that are critical to the hexapod design. Design refinements are outlined by referring to the engineering requirements identified in the preliminary design stage. Thus a design concept of a hybrid leg-wheel hexapod robot is presented in order to show the effectiveness and feasibility of the proposed procedure.

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