A Concept Selection Method for Designing Climbing Robots

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Abstract. This paper presents a concept selection methodology, inspired by the Verein Deutscher Ingenieure (VDI) model and Pugh's weighted matrix method, for designing climbing robots conceptually based on an up-to-date literature review. The proposed method is illustrated with a case study of ongoing research, the investigation of an adaptable and energetically autonomous climbing robot, in Loughborough University.

1 Introduction

Climbing robots are unusual mobile robots that exhibit energy autonomous behavior, have a robust and efficient adhesion mechanism, an agile locomotion mechanism and intelligent sensors integrated together such that they can adapt to various wall surfaces and 3D terrains to conduct given tasks. Climbing robots may be capable of replacing human beings to perform dangerous and tedious operations with high efficiency and low cost for terrestrial and space applications. The health and safety problems can be protected, freeing human beings from risky tasks in hazardous or difficult-to-access environments. Meanwhile, the cost for applying operators or scaffolds can be minimised. Since the seminal work achieved in [1], numbers of climbing robots [2, 3, 4, 5] have been designed to clean high-rise buildings (cleaning), inspect large structures like bridges, solar power plants and confined pipelines etc. (inspection), detect cracks in oil tanks, aircrafts, and nuclear power plants etc. (testing), paint and maintain surfaces of ship hulls, wind turbines and conduct welding for stainless steel tanks etc. (construction and maintenance), deal with anti-terrorism missions or reconnaissance in urban environments (security), and/or for entertainment and education. In addition, climbing robots may be regarded as appropriate vessels for enhancing the autonomy and adaptability of mobile robots, and challenging the boundaries of existing technologies to form coherent systems integrated from diverse technologies.

There are three key issues associated with designing and prototyping this type of robots: 1) adhesion method, 2) locomotion mechanism and 3) actuation mechanism. Climbing robots should be thin and light as thinner ones are harder to peel off from a vertical surface and lighter ones are more stable on the substrate [6]. It is challenging and important to design a proper adhesion method guaranteeing reliable climbing on various wall surfaces whilst not sacrificing flexible mobility and large payloads [2]. Implementing an agile and cost-effective locomotion mechanism is another significant issue associated with climbing robots. For the actuation system of a climbing robot, it would be better to have a large power-to-weight ratio such that climbing robots may enjoy lightweight structures. The proper selection of adhesion method, locomotion mechanism and actuation mechanism should enable climbing robots to have a structure as thin and light as possible.

Although various climbing prototypes have been seen since the 1980s, there is no general engineering recognised design method that can be applicable to designing and prototyping climbing robots. A concept selection methodology for the initial-design-stage of climbing robots is identified and proposed based on an up-to-date literature review in this paper. Also, there is no advanced climbing robot that has full autonomy and adaptability. Most climbing robots have a tethered design or on-board batteries to support themselves. The former method enables robots to have sufficient power; however, the weight of cables and their limited lengths may confine their locomotion capability. The latter method enables robots to have some autonomous behavior. However, most batteries are not good enough to support long-duration tasks. By using energy autonomous systems [7] with novel control methods (such as semantic control [8]), climbing robots may realise long-range, long-endurance missions without the need for manual or conventional re-fueling, and enjoy a high level of energy autonomous behavior like living creatures, and thus the adaptability and autonomy level of robots may be enhanced.

2 Literature Review of Climbing Robots

There are five major categories of adhesion methods in climbing robots that have been summarised in this work and can be seen in Fig. 1. It should be noted that only one representative paper for a certain type was cited although various other papers exist.

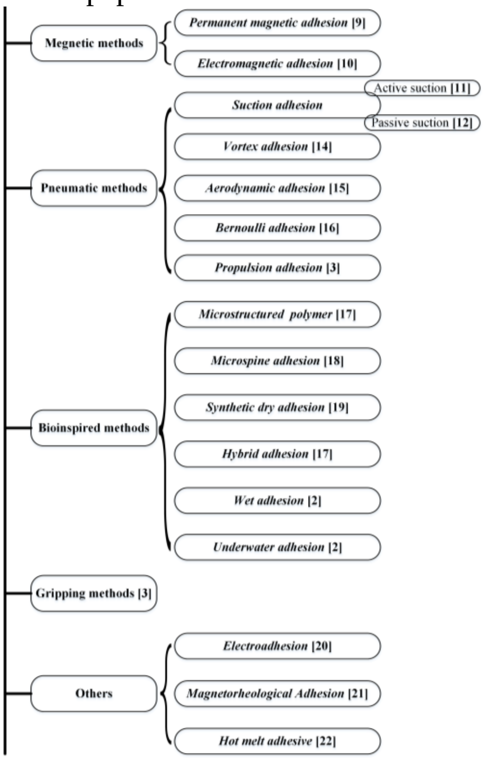

Fig. 1 Adopted adhesion methods in climbing robots

Magnetic adhesion methods [9, 10] may offer fast and reliable mobility and large adhesion forces. However, they are only useful on ferromagnetic surfaces and not energy efficient.

The suction-based adhesion methods comprise active suction methods [11] and passive suction methods [12]. Suction-based climbing robots may climb over surfaces with any material and strong attachment forces, but are only useful on relatively smooth and non-porous surfaces, cannot be used in space applications, noisy, bulky, and comparably high energy consumption, although several improvements, such as a more efficient negative pressure generation mechanism [12] and a noise-less mechanism [13], have been achieved. Vortex adhesion [14], inspired by the tornado, is quieter and more efficient as it does not require sealing devices and aspirators to generate the vacuum. Although an improved version of vortex adhesion, known as aerodynamic attraction, has been proposed [15] to enhance the payload capability and overall mobility, they operate with an unavoidably loud noise, cannot be used in space applications and significant energy consumption still exist. Although Bernoulli-based adhesion, inspired by Bernoulli grippers, suffers from air stream noises and cannot be used in space applications, it has an edge over other methods in terms of high force/weight ratio and good adaptability to various surface conditions [16]. Propulsion-based climbing robots may climb various wall surfaces and are suitable for tasking in large areas with good mobility, but they make a loud noise during operation, have significant energy consumption (usually tens of watts), cannot be used in space applications and are difficult of control [3].

The micro-structured polymer based adhesion method [17] is sensitive to contaminate and dusts, making climbing robots using this mechanism only useful on smooth and clean surfaces. The micro-spine [18] climbing robots are quiet in locomotion, have low energy consumption and are adaptable to hard, dusty, moist and porous surfaces, but they cannot climb on smooth surfaces, overcome large obstacles, and are subjected to plastic deformation and wear. Gecko-inspired synthetic dry adhesives have several advantages, including low energy cost when hanging on walls, quiet and fast in locomotion, reliable in climbing at any orientation and any surface, and suitable for miniaturisation [19]. However, their self-cleaning capability is not mature, making them suffer from contaminate and dusts. Also it is expensive and difficult to prototype robustly. A hybrid adhesion mechanism incorporates several mechanisms together, such as a combination of micro-spines and micro-structured polymer pads [17]. In this way, bio-inspired climbing robots can have greater adaptability to climb on various wall surfaces and conduct complicated wall transitions (such as vertical wall to ceiling transition). However, this method is not mature enough yet and may result in relatively bulky structures. Snail-inspired wet adhesion is rarely used and underwater adhesion climbing robots [2] are specially used in water. They will not be reviewed in this paper.

Gripping-based climbing robots have been prototyped to travel along 3D irregular environments and rough surfaces, such as poles, pipes and bridges, beams and columns, wire meshes, natural environments and manmade structures [4]. However, they cannot be used on smooth surfaces.

Although the adhesion forces generated per unit area by electro-adhesion is relatively weaker compared to other methods, and it may fail in high-moisture environments, electro-adhesion is a promising approach enabling robots to have several advantages, including being adaptable to various wall surfaces, having simpler and lighter structures, being quiet and fast in locomotion and ultra-low energy consumption (usually microwatts) [20]. The magnetorheological fluids (MRFs) based adhesion method enables climbing robots to adapt to a wide range of surface conditions with relatively large clamping pressures [21]. However, the climbing robot adopting this mechanism cannot climb at the moment and some fluids may be left on wall substrates. Hot melt adhesive (HMA) based adhesion can achieve some of the highest adhesion forces (150 newton per square centimeter) and has enabled the robot to have strong adaptability to any solid surfaces and unstructured terrains. However, they are low in speed, have large energy consumption, and usually leave traces behind [22].

With regard to the locomotion mechanisms, five major categories summarised in this work can be seen in Fig. 2.

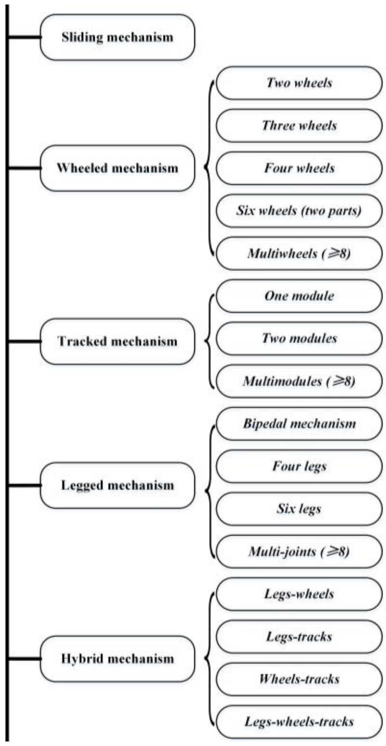

Fig. 2 Adopted locomotion mechanisms in climbing robots

Sliding locomotion mechanisms [3, 23] have enabled climbing robots to control and operate easily compared with other methods as the movement of sliding locomotion is straightforward. However, several inherent drawbacks are striking, such as bulky body size, low speed, and limited ability to cross cracks and obstacles. Wheeled robots [2, 3, 4, 5] can help reach high speeds with lower power consumption and good mobility, but they have limited ability to overcome obstacles. Tracked robots [2, 3, 4, 5] are well suited to uneven and soft terrains with obstacles because the contact with the ground surface is large. However, they are slow in speed and consume more energy than wheeled robots. Legged robots have a broad mobility which makes them suitable for applications both in structured environments and uneven terrains. However, they are relatively slow due to discontinuous movement and they consume a large amount of energy. Also, they are far inferior to that of animals in terms of stability, flexibility, robustness, adaptability and energy efficiency. They are usually driven by many actuators to carry out the complicated gait control to climb robustly. Hybrid-locomotion based robots [2, 3, 4, 5], such as legs-wheels, spoke-wheels, legs-tracks, wheels-tracks, and legs-wheels-tracks, are probably the most interesting solutions as they combine the advantages of the various classes whilst attempting to avoid their drawbacks. However, they have more complicated and heavier structures, and thus are difficult to control.

With regard to the actuation mechanisms for climbing robots, electrical motors account for more than 90% of the adopted actuation mechanisms compared with other three major actuation methods, i.e., hydraulic actuators, pneumatic actuators, and novel-material-based actuators (such as shape memory alloy and piezoelectric transducer actuators) [24]. Also, advantages and disadvantages of these actuation methods have been specified in [24].

3 Proposed Conceptual Design Method

One of the best attempts to indicate the effect of project complexity or size may be the VDI model [25]. Since climbing robots are relatively complex systems and can be divided into several key subsystems aforementioned, a conceptual design selection method inspired by the VDI model is proposed and demonstrated in Fig. 3. It should be noted that this concept method is greatly subjected to user requirements, but is reasonable as any design should satisfy sufficiently with user requirements.

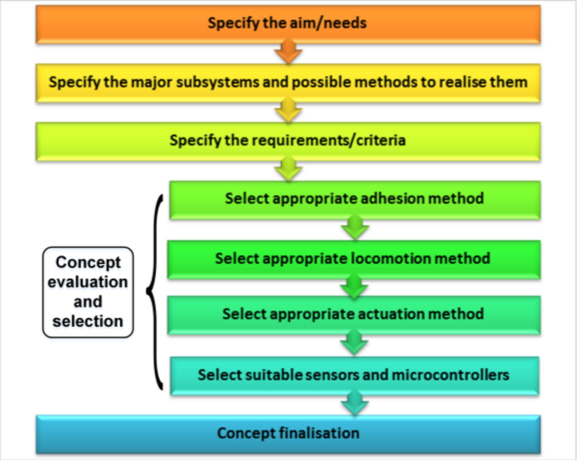

Fig. 3 Proposed conceptual design method

The proposed method starts with specifying the aim or needs to be satisfied as precisely as possible, before specifying the major subsystems and their possible solutions based on functional analysis (such as the functional tree method). Following this, requirements of each major subsystem based on the aim or needs should be specified. Then conceptual selection process using Pugh's weighted matrix method [26] is conducted. The concept finalisation is based on the highest scores using the Eq. 1 given by:

$$\text{Total score}=\sum_{1}^{n} W_n \times D_n \tag{1}$$

where n is the number of alternative concepts, W_n is the importance weighting of nth requirement (based on a 1-5 scale, the higher, the greater the relative importance), and D_n is the rating of the nth requirement (based on a 1-5 scale, the higher, the closer to satisfy the requirements the best).

4 An Example

The investigation of an adaptable and energetically autonomous climbing robot for indoor applications is the aim of ongoing research in Loughborough University. The major subsystems should contain appropriate adhesion system, locomotion system, actuation system, energy autonomous system and sensing and control system. The requirements are listed in Table 1, where score 5 stands for the highest priority, whilst score 1 stands for the lowest priority.

Table 1 Requirements in designing the climbing robot

Requirements		Score
Adhesion system	Climb reliably on smooth and non-ferrous surfaces	5
	Easy to manufacture/realise	5
	High adhesion force	5
	Efficient attach and detach mechanism	5
	Quiet	5
	Low energy cost when attaching	5
	Low energy cost when detaching	5
	Reusable	5
	No residue	4
	Adaptable to rough surfaces	3
	Adaptable to different wall materials	3
	Technology readiness	3
	Enable climbing robots to be light weight	3
	Enable climbing robots to be small or simple in structure	3
	Low cost	1
Energy autonomy system	Easy to manufacture/realise	5
	High energy efficiency	5
	Easy to integrate	5
	Suitable for indoor application	5
	Robust	5
	High energy density	4
	Technology readiness	4
	Light weight	4
	Small in size	3
	Low cost	1
Locomotion system	High capability to make 3D transitions	5
	Enable efficient attachment and detachment	5
	Low energy cost	4
	Technology readiness	4
	Easy to control	3
	Fast	3
	Enable climbing robots to be light weight	3
	Enable climbing robots to be small or simple in structure	3
	High obstacle crossing capability	2
	High turning capability	1
	Low cost	1
Actuation system	Easy to control	5
	Easy to integrate	5
	No residue	5
	Technology readiness	5
	Enable climbing robots to be light weight	3
	Enable climbing robots to be small or simple in structure	3
	Low cost	1
Sensing and control system	Robust	5
	Easy to integrate	5
	Novel and adaptable	5
	Technology readiness	4
	Light weight	3
	Low cost	1

The next step is to select the most appropriate adhesion methods, locomotion methods, actuation methods and suitable sensors and control methods based on the requirements. According to the process described above, the weighted matrix to choose appropriate adhesion methods according to the requirements is demonstrated in Table 2. Based on the scores, electro-adhesion is the best choice. Please note that the adhesion method will not be considered when it scores 0, even though it may earn a high total score based on the Eq. 1.

Table 2 Selection of an adhesion mechanism using weighted matrix

			Adhesion mechanisms																
		Importance weighting	Common/active suction	Vibrating suction	Vortex adhesion	Aerodynamic attraction	Bernoulli based	Propulsion adhesion	Permanent magnetic	Electro magnetic	Gripping based	**Electro adhesion**	HMA	MRFs	Snail inspired	Micro structured polymer	Micro spines	Synthetic dry adhesives	Hybrid (bio-inspired)
Requirements	Climb reliably on smooth and non-ferrous surfaces	5	5	5	5	5	5	5	0	0	0	**5**	5	5	5	5	0	5	4
	Easy to realise	5	5	2	4	4	3	5	5	4	2	**4**	4	2	2	4	3	2	1
	High adhesion force	5	4	4	2	3	2	5	5	5	4	**4**	5	2	2	4	4	3	3
	Efficient attach and detach mechanism	5	3	2	3	3	3	3	2	3	4	**5**	1	3	2	3	5	5	5
	Quiet	5	1	2	1	1	1	1	5	5	5	**5**	5	5	5	5	5	5	5
	Low energy cost when attaching	5	1	2	1	1	1	1	5	1	2	**4**	1	3	3	5	4	5	5
	Low energy cost when detaching	5	5	2	5	5	5	5	2	1	5	**5**	1	5	3	2	4	4	4
	No residue	4	5	5	5	5	5	5	5	5	5	**5**	1	2	1	5	5	5	5
	Reusable	5	5	5	5	5	5	5	5	5	4	**5**	1	2	2	1	2	1	2
	Adaptable to rough surfaces	3	3	1	5	5	5	5	5	5	3	**5**	5	4	2	2	4	2	2
	Adaptable to different wall materials	3	5	3	5	5	5	5	1	1	5	**5**	5	5	3	3	5	4	4
	Technology readiness	3	5	1	3	2	1	5	5	5	4	**4**	5	2	1	5	2	2	1
	Enable climbing robots to be lightweight	3	1	3	2	2	4	1	3	4	4	**4**	2	3	5	5	5	5	4
	Enable climbing robots to be simple in structure	3	1	5	2	2	4	2	3	3	3	**5**	3	3	2	5	4	4	4
	Low cost	1	1	1	1	1	1	2	2	3	2	**5**	5	3	1	5	5	1	1
Total Score			211	180	202	204	203	226	222	197	209	**279**	184	197	164	230	220	222	211

Similarly, it can be seen that a double-tracked (two modules) locomotion mechanism and electrical motors (together with some range sensors controlled by a Microchip PIC18F458 controller) as the actuation method should be selected. With regard to the autonomous energy harvesting system for the proposed climbing robots, wireless energy transfer (especially electrostatic induction based) method should be selected amongst the three potential methods stated, i.e., solar power method, wireless energy transfer method [27] and bio-inspired energy foraging method [28]. Semantic control method and a Vicon tracking system are selected for the climbing robot to overcome 3D obstacles during indoor climbing and conduct complicated transitions.

5 Summary

In summary, based on the presented concept selection method, the proposed energetically autonomous climbing robot will adopt electro-adhesion as its adhesion method, double-tracked mechanism as its locomotion method, electric motors as its actuation method, wireless energy transfer method as its energy autonomous method, and the semantic control method. A conceptual diagram of the proposed climbing robot can be seen in Fig. 4, where the tail with a force sensor can be useful for preventing the peeling effect, the double-tracked mechanism is useful for some complicated wall transitions, the rotating holder enables the high voltage converters to rotate with the electro-adhesive pad modules, the energy receivers connected with the high voltage converters can provide power for the pads and the range sensors enable the climbing robot to overcome 3D obstacles during climbing.

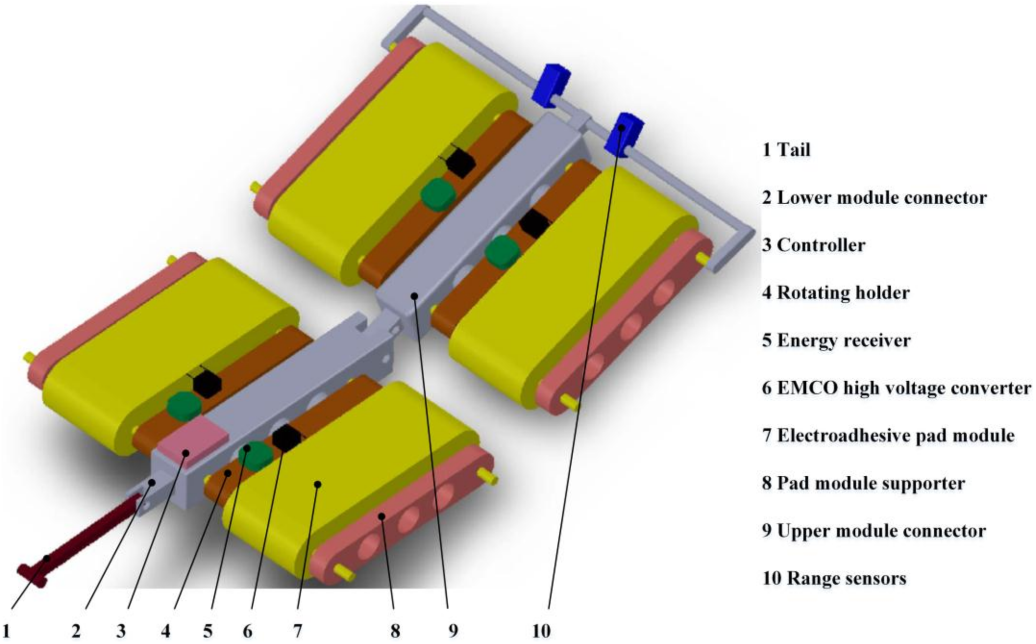

Fig. 4 Conceptual model of the proposed climbing robot

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