CLIMBING WITH STRUCTURED DRY ADHESIVES: STICKY ROBOTS FOR SCALING SMOOTH VERTICAL SURFACES

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ABSTRACT

Two styles of climbing robot were developed for space applications. These robots, which used gecko-like dry adhesives for adhesion, have the potential to stick to nearly any surface in low pressure environments (unlike magnets, suction cups or pressure sensitive adhesives). TBCP (Timing Belt Climbing Platform), a 240 g robot, consisted of two modules and used belts of dry adhesive to adhere to the wall. A method of preloading the front module using the rear module was developed. Vertical climbing was performed at a speed of $34\,\mathrm{mm\,s^{-1}}$ and transfers between various orthogonal surfaces were demonstrated. Three prototypes of a legged robot, Abigaille, were built. Two Abigaille prototypes could climb vertically ($1\,\mathrm{mm\,s^{-1}}$ for Abigaille-II and $0.4\,\mathrm{mm\,s^{-1}}$ for Abigaille-III) and transfer from horizontal to vertical surfaces. With more strength than the other Abigaille prototypes, Abigaille-III was also capable of traversing structured surfaces and overcoming small obstacles while climbing.

Key words: Climbing robot; dry adhesives; bio-inspired, space.

1. INTRODUCTION

Robotic systems are candidates for use where it would be unsafe or high-risk for a human to work. In space, an example of a high-risk task is robotic inspection and repair on the exterior of an orbiting satellite, where a robot must adhere to the satellite's exterior. A robot in space has a stricter adhesive requirement than a robot on earth: the adhesive cannot outgas, it must stick robustly to various surfaces, must work in vacuum and preferably be passive [1]. One adhesive with these properties is a gecko-inspired synthetic dry adhesive [2, 3, 4, 5, 6, 7]. One style of synthetic dry adhesive, suitable for integration on a climbing robot, consists of an array of micro-scale mushroom caps on a Polydimethylsiloxane (PDMS) substrate [2, 6, 7].

Robots using dry adhesives for vertical climbing have previously been developed. Some of these robots mimic the shape and form of a gecko, for example the Rigid Gecko Robot and Compliant Gecko Robot [8], Geckobot [9] and Stickybot [10]. While the other gecko-shaped robots are not capable of vertical climbing (e.g. Geckobot can only ascend 85° slopes), Stickybot climbs vertically at $40\,\mathrm{mm\,s^{-1}}$. Though the legged design of these gecko-inspired robots has the potential to be dexterous and allow the robots to overcome uneven terrain, so far this style of robot has only been demonstrated on smooth surfaces.

Climbing robots with continuous adhesive tracks have also been developed [11, 12]. Tankbot [11] uses elastomer adhesives for vertical climbing, transitioning between surfaces and loitering inverted on a ceiling. An active tail helps Tankbot to preload its adhesives while climbing vertically. MaTBot [12] uses a combination of magnets and dry adhesives for climbing vertically on ferromagnetic surfaces, however with only dry adhesion the maximum slope MaTBot can traverse is 60°. Continuous tracked robots are capable of fast locomotion on smooth surfaces, and overcoming small obstacles, however they requires a tail for preloading, which can get in the way while transitioning between surfaces.

To demonstrate the use of gecko-inspired dry adhesives for climbing robots, two styles of robots, capable of scaling smooth vertical surfaces, were developed. The first type of robot was an articulated tank-tracked robot named TBCP (Timing Belt Climbing Platform) [13], designed for applications in which greater speed and movement range is needed, for example planetary exploration. Compared to previous prototypes, TBCP has the advantage of not needing a tail (a tail adds extra mass and complexity, and can get in the way during inside transitions). The second type of robot presented (Abigaille [14, 15]) is a legged hexapod, designed for applications requiring increased mobility, for example inspection and repair of an orbiting spacecraft. Unlike previous legged robots, the Abigaille-III robot demonstrated dexterity by climbing on uneven surfaces and transferring between orthogonal surfaces.

In Section 2 the adhesive system of each robot is described in detail. Next, in Section 3 and Section 4, the mechanical and electrical subsystems of the TBCP and Abigaille robots, respectively, are described. In Section 5, the main capabilities of each robot system are described. Finally, conclusions and future work are outlined in Section 6.

2. ADHESIVE SYSTEMS

The TBCP and Abigaille robots stick to smooth surfaces using dry adhesives manufactured from PDMS. Manufacturing adhesives was done using the method described by Sameoto and Menon [2]. PDMS was poured onto a patterned silicon wafer with a surface area of about 7000 mm^2. After degassing in vacuum, the PDMS was cured at 80 °C for 3 h. The PDMS adhesive was then demoulded from the wafer. For integration onto the foot of an Abigaille robot, or to form the continuous track of a TBCP robot, further fabrication processes were necessary.

2.1. TBCP adhesive integration

To make adhesives for integration on a TBCP robot, as described by Krahn et al. [13], the demoulded PDMS adhesive was first cut into squares with a side length of 40 mm. Five squares were cut and laid side-by-side on a flat Poly(methyl methacrylate) (PMMA) surface, forming a rectangle with side lengths of 40 mm and 200 mm. The adhesives were then reinforced using 30 gauge copper wire; equally spaced lengths of wire were laid on the PDMS along the length of the rectangle (see Fig. 1). These wires were secured in place with additional PDMS which was degassed in a vacuum, and poured over the rectangle. The PDMS and wire reinforcement served to bond the individual squares together, and prevent the adhesive from stretching. Finally, the rectangle was trimmed to length (183 mm), joined at its ends with additional PDMS (10:1 ratio), and cut in half to make two identical belts of 20 mm width. A completed belt is shown in Fig. 1. These belts were placed over rubber timing belts, which were secured on the continuous track TBCP robot using a self-tensioning spring system.

2.2. Abigaille adhesive integration

The design of an adhesive foot for a legged climbing robot poses a number of challenges. The adhesive has a relatively small area (compared to a continuous track adhesive), and yet must support a substantial normal-direction force to hold the robot on the wall. As the robot moves, each foot must stay attached to the climbing surface, requiring some passive or active degrees of freedom near the attachment point. A method of orienting the foot against the climbing surface so that the adhesive is brought in contact with the surface at each step is essential. Finally a method for detaching the adhesive foot is needed each time a step is taken.

Each Abigaille robot had slightly different adhesive foot pad and foot designs. Abigaille-I used unpatterned PDMS, and relied on friction between PDMS and smooth

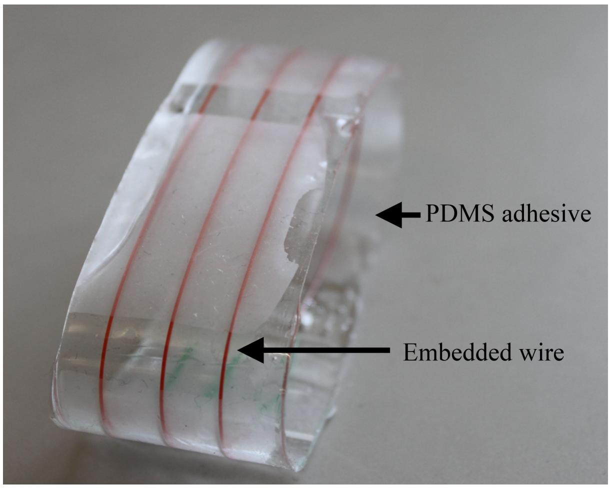

Figure 1. An adhesive belt used on the TBCP robot, which shows the embedded wires in a PDMS adhesive.

surfaces to adhere each foot in place. Abigaille-II and -III used synthetic dry adhesive fabricated in the method described in Section 2.1 [2].

Abigaille-I had round feet made of unpatterned PDMS, as described by Menon et al. [15], and shown in Fig. 2a. First, a mould was made from fused plastic on a 3D printer. PDMS was mixed 10:1, poured into this mould and degassed. Each foot was bonded to a robot's leg using additional PDMS, forming a compliant, 3-DOF, ankle joint. Because the PDMS had inherent stiffness, it always oriented itself in a specific direction when unloaded. The use of a specific trajectory was sufficient to position the foot normal to a surface when attaching. Because the PDMS was not patterned, and therefore had negligible normal-direction adhesion, detaching was not a challenge for this version of Abigaille.

Abigaille-II had a hierarchical, PDMS adhesive foot, described by Li et al. [14] and shown in Fig. 2b. First, a 100 mm^2 array of PDMS posts (macro-posts) was moulded [16]. The macro-post array contained square posts with a width of 1 mm, a height of 3 mm and inter-post spacing of 3 mm. This layer was reinforced with a cotton cloth. Next, a section of PDMS dry adhesive was cut to be larger than the the post array. The dry adhesive was bonded (adhesive side out) to the macro-posts, overhanging to one side of the macro-posts, using a thin layer of PDMS mixed 10:1. Finally, the exposed side of the macro-posts was bonded to a fused plastic robot leg using hot glue (forming a compliant bond). Similar to the feet of Abigaille-I, the compliant ankle bond of each of Abigaille-II's feet allowed the robot to move without detaching its feet, and allowed a trajectory based-positioning method to be employed. Because Abigaille-II used adhesives, detaching each foot (before moving it to a new position) was necessary. Because the adhesives were flexible, specific trajectories were used to peel the adhesive from the climbing surface.

Abigaille-III was a heavier robot than Abigaille-I or -II,

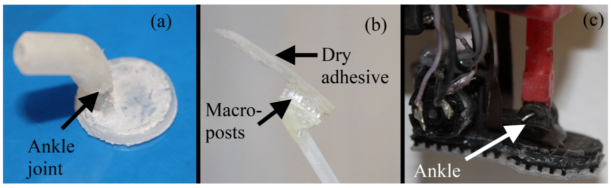

Figure 2. Footpads of the three Abigaille robots. In (a), the solid PDMS footpad, and compliant ankle joint, of Abigaille-I is shown. In (b), the dual-layer adhesive of Abigaille-II is shown, with the macro-posts and dry adhesive flap indicated. The footpad of Abigaille-III (c) contains only a single DOF ankle joint.

and therefore required different strategies for its foot design. A hierarchical PDMS adhesive structure was built by bonding a layer of macro-posts to dry adhesive using Dow Corning 732 (a silicone compound). The macro-posts were then bonded to a rigid, fused plastic foot. The foot was attached to a leg of the robot using a 1-DOF rotational joint, allowing forward movement without causing the foot to detach (see Fig. 2c). Abigaille-III's feet were larger (400 mm^2 each) than the feet of Abigaille-II, supporting the additional mass of Abigaille-III. The use of an overhanging adhesive flap was not feasible because the mass of Abigaille-III caused this flap to spontaneously detach. Instead, each foot was strongly preloaded against the climbing surface following each step. To detach a foot, a motor and cam were integrated into each foot. The cam rotated and pried the adhesive foot off the surface, causing it to detach. To ensure the foot returned to the proper position for reattaching, an elastic band was connected between the rigid foot and one of the leg segments.

3. TIMING BELT CLIMBING PLATFORM

The TBCP robot was a continuous track robot, providing a large adhesive area for sticking to smooth surfaces. Two modules were used, meaning that the use of a tail could be avoided (the rear module could perform the functions of a tail). The electronics were responsible for ensuring that the adhesives remained preloaded during climbing.

3.1. Mechanical design

The two modules of the TBCP robot were connected by a center joint (see Fig. 3). The frame of the robot was made from aluminum and fused plastic. Each module contained two continuous tracks, which adhered the robot to the wall. One motor was used to drive each track, and three motors were used to control the position of the center joint. Potentiometers resolved the speed and direction of the drive motors, as well as the position of the center joint. Short range (5 to 30 mm) proximity sensors detected the height of the frame from the climbing surface, while long range sensors (30 to 300 mm) helped to position the robot relative to a wall when it transferred between orthogonal surfaces. The TBCP robot had a mass of 240 g.

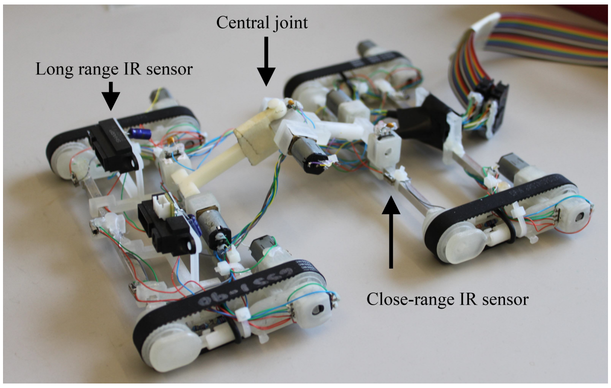

Figure 3. The TBCP robot on a horizontal surface with the adhesive belts removed. The robot consists of two modules, connected by a center joint. Long-range IR sensors are used to provide the robot information about its surroundings, and close-range IR sensors indicate the degree of adhesive preload.

3.2. Electronics and software design

A Digital Signal Processor (DSP), as shown in Fig. 6a, was used by TBCP to process sensor signals and control motor speeds during climbing. A custom LABView program ran on a Personal Computer (PC) and sent high-level commands wirelessly using a Zigbee protocol to the DSP.

The ADCs on the DSP collected and digitized analog sensor values at 20 MHz. When the robot was stationary, the IR sensors recalibrated themselves, compensating for any changes in ambient light. During vertical climbing, the control system acted to ensure that the IR sensors aimed towards the climbing surface read equal values, indicating that the robot was parallel to the wall. Deviations from parallel were signs of adhesive detachment, and were corrected by preloading actions. To perform a preloading action, the center joint was rotated to bring either the front or rear section into better contact with the wall. The TBCP was also capable of transitioning between orthogonal surfaces. To do so, the center joint was rotated to allow the modules to independently approach and transition between surfaces. Preloading was conducted throughout the transition.

4. ABIGAILLE

All versions of the Abigaille robot had a hexapod configuration. The six legged configuration was chosen as a compromise between complexity (more legs are harder to control) and safety (a robot with more legs attached to the wall is less likely to fail).

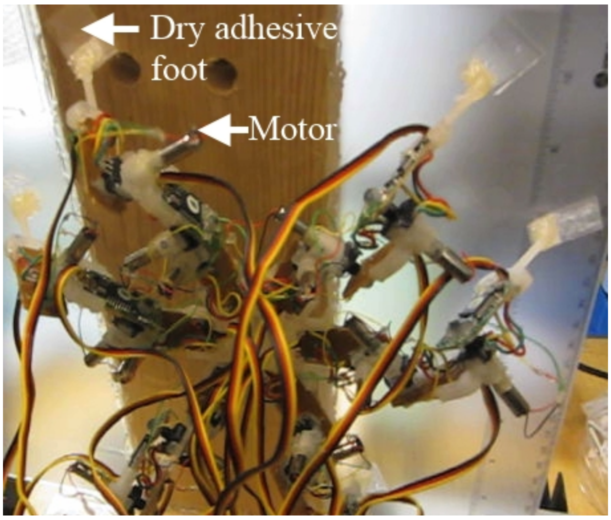

Figure 4. Abigaille-II climbing a vertical wall. The servo controller is not visible in this photo.

4.1. Mechanical design

Abigaille-I [15] was made substantially from fused plastic. The legs were arranged in a circular fashion around the electronics, which were mounted on top of the body. Three active joints were used for each leg; each joint was controlled by a DC gear motor and measured with a Hall effect sensor. The robot's total mass was 131 g.

Abigaille-II (see Fig. 4) [14] retained the circular leg arrangement and joint configuration of Abigaille-I. To reduce mass and increase body stiffness, the Printed Circuit Boards (PCBs) were incorporated into the mechanical structure of each leg. Each joint was controlled by a DC gear motor (200 g cm of torque), and joint positions were sensed with linear rotary potentiometers. Abigaille-II had a total mass of 260 g, and was made mainly of fused plastic.

Abigaille-III (see Fig. 5) had a rectangular body and legs positioned in an orientation that was determined by Li et al. [14] to be close to the optimal orientation for climbing. The joint configuration of Abigaille-III was the same as previous Abigaille robots. Each joint was controlled by a DC gear motor (1800 g cm of torque) and joint positions were sensed with linear rotary potentiometers. The legs were made from fused plastic and the frame was cut on a laser cutter from PMMA. The electronics of Abigaille-III were mounted below the body, in order to keep the center of mass low. The total mass of Abigaille-III was 650 g.

4.2. Electronics design

Abigaille-I had custom electronics, based around a microcontroller [15], as shown in Fig. 6b. The 18 DC motors were controlled by H-Bridge motor drivers, connected to the microcontroller with shift registers. The signals from the Hall effect sensors were conditioned with an op-amp, buffered, and multiplexed to the ADC on the microcontroller.

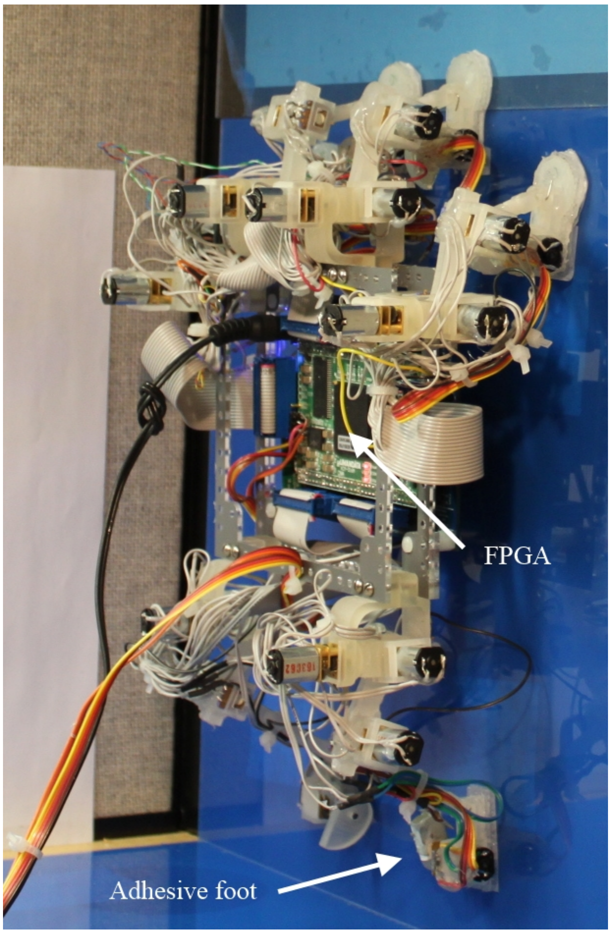

Figure 5. Abigaille-III climbing a vertical wall. The FPGA computing system is mounted in the center of the body. Six adhesive feet are arranged around the body.

To increase ease of programming, Abigaille-II had electronics based around a servo controller [14], as shown in Fig. 6c. Commands from a PC were sent wirelessly via a Bluetooth protocol to a servo controller on the robot. This servo controller commanded each joint of the robot, ensuring that each target position was met. Sequences of commands were used to perform walking or climbing motions.

One problem with the use of a servo controller for Abigaille-II was the inflexibility of the electronics system. Excessive vibrations were noted upon detachment of individual feet, however damping the vibrations was not feasible. In Abigaille-III, a Field Programmable Gate Array (FPGA) (see Fig. 6d) was used as the computing system in order to provide the user more flexibility [17]. At the low level, a proportional-gain controller was implemented to control joint positions. At the high level, preloading and detaching strategies were developed. The electronics of Abigaille-III were also custom. A PCB containing motor drivers and ICs to condition the analog potentiometer signals was designed and implemented.

5. RESULTS

Each robot demonstrated different capabilities. The TBCP robot was relatively fast, but limited in the types of surfaces it could climb. In contrast, the Abigaille robots showed more dexterity, but were heavier and slower. The TBCP robot moved at $34\,\mathrm{mm\,s^{-1}}$, Abigaille-II moved at $45\,\mathrm{mm\,s^{-1}}$ horizontally and $1\,\mathrm{mm\,s^{-1}}$ vertically, and Abigaille-III moved at $1\,\mathrm{mm\,s^{-1}}$ horizontally and $0.4\,\mathrm{mm\,s^{-1}}$ vertically. For transferring operations, the Abigaille-II and -III robots transitioned from a horizontal to vertical (inside) corner, while the TBCP robot performed both inside and outside transitions from horizontal to vertical (and vice-versa). Abigaille-III was capable of walking vertically up uneven surfaces, as each of its legs was capable of being at different distances from its body, unlike the tracked TBCP. These metrics are summarized in Tab. 1.

Table 1. Performance metrics for the climbing robots.

	Abigaille I	Abigaille II	TBCP
Horizontal speed ($\mathrm{mm\,s^{-1}}$)	45.0	1.0	34
Vertical speed ($\mathrm{mm\,s^{-1}}$)	1.0	0.4	34
Inside transfer	x	x	x
Outside transfer			x
Uneven surface		x	

6. CONCLUSIONS

Four robots were prototyped and presented. The robots were designed for vertical climbing using dry adhesives. The TBCP robot consisted of two modules connected by a center joint. Adhesive belts containing outward-facing synthetic dry adhesive enabled this robot to adhere to and climb smooth surfaces. The TBCP robot moved quickly ($34\,\mathrm{mm\,s^{-1}}$) on both horizontal and vertical surfaces. The Abigaille-series robots were legged, hexapod robots. Dry adhesive footpads allowed the Abigaille robots to stick to smooth surfaces. While the Abigaille robots were slower ($0.4\,\mathrm{mm\,s^{-1}}$ to $1.0\,\mathrm{mm\,s^{-1}}$ on vertical surfaces), they had more dexterity and were able to traverse uneven surfaces.

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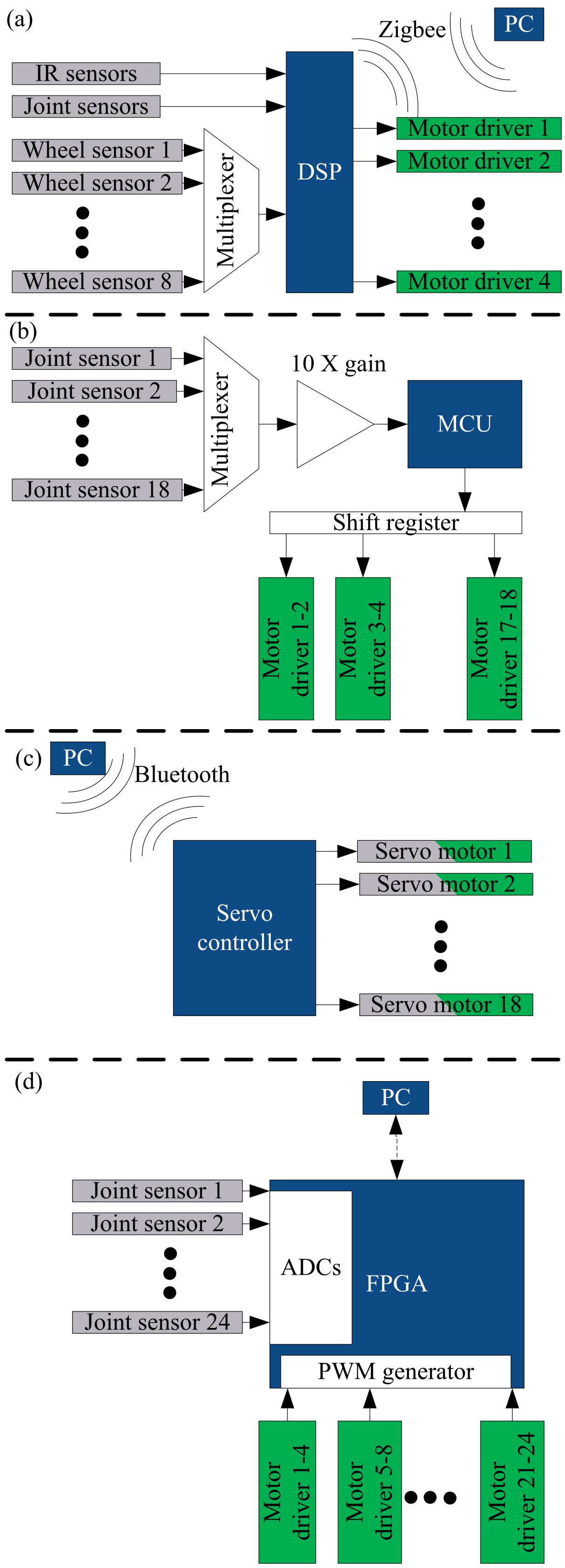

Figure 6. Computing systems for the TBCP (a) and Abigaille (b-d) robots.

REFERENCES

1. Menon, C., Murphy, M., Sitti, M., and Lan, N. Space exploration - towards bio-inspired climbing robots. In Habib, M. K., editor, *Bioinspiration and Robotics: Walking and Climbing Robots*, chapter 16, pages 261–278. InTech, 1 edition, 2007.

2. Sameoto, D. and Menon, C. A low-cost, high-yield fabrication method for producing optimized biomimetic dry adhesives. *Journal of Micromechanics and Microengineering*, 19(11):115002, November 2009.

3. Santos, D., Kim, S., Spenko, M., Parness, A., and Cutkosky, M. Directional Adhesive Structures for Controlled Climbing on Smooth Vertical Surfaces. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 1262–1267, Roma, Italy, April 2007. IEEE.

4. Sitti, M. and Fearing, R. S. Synthetic Gecko Foot-Hair Micro / Nano-Structures as Dry Adhesives. *Journal of Adhesion Science and Technology*, 18(7):1–16, 2003.

5. Sethi, S., Ge, L., Ci, L., Ajayan, P. M., and Dhinojwala, A. Gecko-inspired carbon nanotube-based self-cleaning adhesives. *Nano letters*, 8(3):822–5, March 2008.

6. Sameoto, D. and Menon, C. Direct molding of dry adhesives with anisotropic peel strength using an offset lift-off photoresist mold. *Journal of Micromechanics and Microengineering*, 19(11):115026, November 2009.

7. Davies, J., Haq, S., Hawke, T., and Sargent, J. A practical approach to the development of a synthetic Gecko tape. *International Journal of Adhesion and Adhesives*, 29(4):380–390, June 2009.

8. Menon, C. and Sitti, M. A Biomimetic Climbing Robot Based on the Gecko. *Journal of Bionic Engineering*, 3(3):115–125, September 2006.

9. Unver, O., Uneri, A., Aydemir, A., and Sitti, M. Geckobot: a gecko inspired climbing robot using elastomer adhesives. In *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, pages 2329–2335, Orlando, Florida, 2006. IEEE.

10. Spenko, M., Trujillo, S., Heyneman, B., Santos, D., and Cutkosky, M. Smooth Vertical Surface Climbing With Directional Adhesion. *IEEE Transactions on Robotics*, 24(1):65–74, February 2008.

11. Unver, O. and Sitti, M. Tankbot: A Palm-size, Tank-like Climbing Robot using Soft Elastomer Adhesive Treads. *The International Journal of Robotics Research*, 29(14):1761–1777, September 2010.

12. Fremerey, M., Gorb, S., Heepe, L., Kasper, D., and Witte, H. MaTBot: A Magnetoadhesive Track robot for the inspection of artificial smooth substrates. In *AMAM*, pages 19–20, 2011.

13. Krahn, J., Liu, Y., Sadeghi, A., and Menon, C. A tailless timing belt climbing platform utilizing dry adhesives with mushroom caps. *Smart Materials and Structures*, 20:1–11, 2011.

14. Li, Y., Ahmed, A., Sameoto, D., and Menon, C. Abigaille II: toward the development of a spider-inspired climbing robot. *Robotica*, 30:79–89, April 2012.

15. Menon, C., Li, Y., Sameoto, D., and Martens, C. Abigaille-I: Towards the development of a spider-inspired climbing robot for space use. *2008 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, pages 384–389, October 2008.

16. Li, Y., Sameoto, D., and Menon, C. Enhanced Compliant Adhesive Design and Fabrication with Dual-Level Hierarchical Structure. *Journal of Bionic Engineering*, 7(3):228–234, September 2010.

17. Henrey, M., Edmond, S., Shannon, L., and Menon, C. Bio-inspired walking : A FPGA multicore system for a legged robot. In *Field Programmable Logic and Applications (FPL), 2012 22nd International Conference on*, pages 105–111, Oslo, 2012.