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PetRo: development of a modular pet robot

Ben Salem, *Member, IEEE*

***Abstract*— Modular robots present many advantages that open opportunities for novel applications and greater variability in operational parameters. We present PetRo (which stands for Pet Robot) as a modular throwable, self-assembling and reconfigurable pet robot. Some of the design challenges and solutions selected are explained as well as the two main applications for which the robot architecture is being developed: namely as a companion pet and for search and rescue operations. Although both applications are being considered, this paper places emphasis on the first and the potential for human robot interactive communication is highlighted.**

I. Introduction

Homogeneous modular robots (HMR) are defined as robotic systems that are made up of an assembly of identical units or modules. The main benefit of HMR is the provision of redundancies in the robot as a system, allowing modules, to be interchanged in case of failure of one of them - a benefit that is further enhanced when the robot is also reconfigurable. In such a case, the robot can perform the replacement of faulty modules autonomously, but it can also adopt different configurations, and thereafter a different overall shape, to deliver changes in gait, mobility and dexterity.

We are interested, within the scope of our work on modular robots, in systems that are modular homogeneous and reconfigurable, but also self-assembling and throwable. The latter two requirements imply that a number of isolated single modules are capable of regrouping and self-assembling into a desired configuration within the theatre of operations. This also imply that each module does not require particular handling, and that it is sufficiently robust to be literally thrown into the theatre of operation. We see this as necessary and desirable for pet applications.

A. A brief perspective on modular robots

The origin of modular robots can be traced to CEBOT [1], and Polypod [2]. Both have contributed to make the concept of reconfigurable modular robots a reality. Since then, there have been many developments in the area, notably [3-7]. Modular robots can be classified as homogeneous or heterogeneous systems, depending on whether the system is made of identical repeating modules or of an assembly of specialised modules. Interestingly all developments in HMR have resulted in modular robots that require an assembly of a minimum number of modules for the system to become an operational robot. PetRo design, is a direct response to this and is an attempt at delivering a HMR where single isolated modules are operational robots in themselves.

Another interesting aspect of modular robots is the repetitive pattern that is intrinsic to this type of robots. It is interesting because it creates a challenge in terms of the suitability of such robots for applications where non-verbal communication and expressions towards humans are desirable. The challenge here is to come up with a modular architecture that allows for assemblies that can be somewhat expressive. To do so we have taken as a guiding principle that assemblies of modules should be zoomorphic and ideally resemble a pet.

In the remainder of the paper, we will describe the rationale behind the design of PetRo, explain its key features and then expand on its potential for pet-like dialogues. We conclude with current and future works.

II. PetRo as a Modular Robot

A. Origins of the concept

PetRo was specified and designed as a modular robot based on a caltrop shape and possessing both high mobility and omni directionality. The name stand for Pet Robot and this was intended to illustrate our aim to deliver a robotic platform with multiple applications including companion pet, search and rescue, and in general applications where it is difficult to predict the theatre of operation in which the robot will be used. The concept was first presented in [8], and we are developing the concept into a series of demonstration prototypes (the current version being developed is the third generation).

The main motivation behind the project was the need to deliver a robotic platform that allows for field applications away from controlled environments (notably where surfaces of operation are smooth and regular). Such an allowance requires both reconfigurability and high-mobility. We also wanted to minimise the handling and care required by the robot, aiming, in the long term, for a throwable robot (from up to 2 meters). A secondary motivation was our interest in developing a pet-like robot similar to the SONY AIBO but without the limited mobility due to the small gait, an inherent outcome of the overall architecture of the robot. Finally, we were seeking a design that allow even a single isolate module to be a mobile and usable robot.

B. The implications of a modular approach

A modular approach offers many benefits, first and foremost, the availability of redundancies allowing for damaged modules to be discarded, thus improving reliability. This redundancy is also a contributor to addressing a potentially constraining limited power supply, by allowing the re-distribution of power amongst modules. A second benefit is the adaptability of the robot that goes as far as reconfigurability in terms of overall architecture and thereafter offer variability in gaits and motions available. A third benefit, specific to the pet application, is the metaphoric growth potential the robot possesses by adding modules to the assembly. An interesting fact from a commercial perspective.

B. SALEM is with Northumbria University, UK & The University of Amsterdam, NL (phone: +44 7971 199164; e-mail: mail@bsalem.info).

III. Overall Design

The overall design of PetRo was inspired from concrete tetrapods (shaped like a caltrop) visible at a harbour's jetty (see figure 1). Such a shape has the advantage of being omni-directional and allowing for throw-ability, since which ever way the tetrapod lands, it is always the right way up. Indeed, the design present a peculiarity, there is no preferred direction nor is there a sense of up and down.

Figure 1. Concrete tetrapods, the design inspiration.

The caltrop shape has also a connection to chemistry for modelling molecules, and makes assemblies possible along each of the axis. Finally, the shape is quite abstract and aesthetically relevant to the proposed applications, in particular it can be perceived as a metaphor for a skeleton. Accordingly, PetRo was designed with rotational symmetry around a central hub and four legs equidistantly distributed around it's circumference. As a property of omni-directionality, each each of PetRo's leg can be replaced by any other.

A. *Joints & degrees of freedom*

To ensure the highest adaptability and reconfigurability possible, at the connection between the central hub and each leg, there are two types of joints with one degrees of Freedom (DOF) each, called hub and shoulder. At the end of each leg there is one terminal joint with one DOF, a wheel to which is attached a connecting terminal (see figures 2 &3).

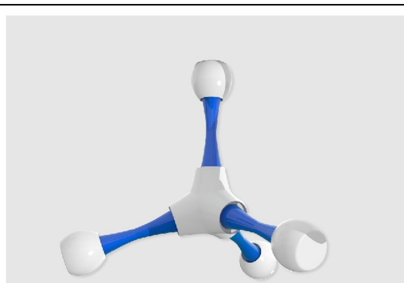

Figure 2. Single module model CAD version 1

The hub joint is a rotation joint along the leg axis that allows for a complete rotation of 360 degrees. There is also a rotation joint, called a shoulder joint, perpendicular to the leg axis that can rotate ±45 degrees. The terminal joint on each leg is a wheel rotation. All joints are actuated by stepper motors and corresponding control circuitry. In the current version of the robot build (2nd generation), joints are driven by a combination of cog wheels transmitting power from the motors.

B. *Mobility & Gait of a Single Module*

In the case of a single isolated module, at any one point there are three legs on the ground, therefore, the robot can move in the following ways: rotation (where all wheels are rotating in the same direction), and translation (where two wheels are rotating in symmetry and a third one is trailing). In such a case, the upward leg, metaphorically represents the "head" of the robot and therefore can perform some body movements through rotations of each of the joints (table I).

TABLE I. Mobility of Single Isolated Module

Joints	**Degrees of Freedom**		
	Details	***DOF***	***Axis***
hub	Connecting leg to central hub	2	Around leg axis, and perpendicular to leg axis
Wheel	Provides motion to the robot, acts as connecting terminal	1	Around leg/wheel axis

Such mobility is one of the key features of the design of PetRo is the fact that isolated, single modules are operational robots that can move around, albeit in a reduced capacity. This is a preeminent feature amongst HMR.

Figure 3. Single module model CAD version 2

IV. Fabrication of the Module Prototypes

Since the inception of the robot, we have adopted an iterative design process, and we are now for the third time designing the robot as a whole, taking into account lessons learned, and implementing more astute mechanical designs. Figure 4, left show the first prototype of the robot, while the right picture show the second version. Details of this version are also illustrated in figure 5.

The first prototype of the module was built to evaluate general design and feasibility. The prototype was very simple in terms of actuation and relied on DC motors for a demonstration of concept (see figure 4,left). The body of the robot was vacuum formed. There was two joints for each leg: A hub joint and a wheel joint, both having one DOF. The parts were directly attached to the DC motor rotors, without bearings or gears.

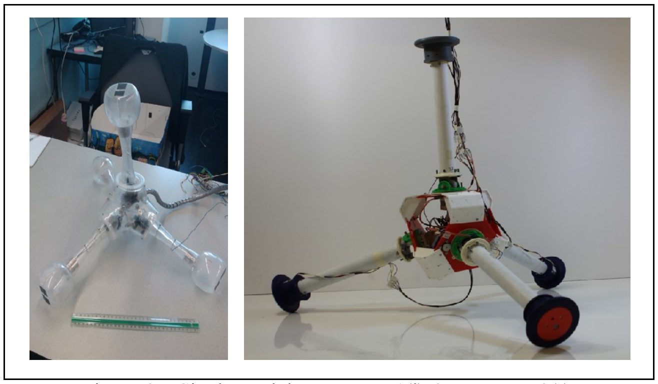

Figure 4. Single module prototype 1(l) & prototype 2(r)

Prototype two of the robot was built with a significantly more complex design, taking into account the lessons from the previous version and was our first attempt at building a demonstrator of the design (see figure 4, right). This prototype allowed us to gain valuable insights into the mechanical and control issues pertaining to the design, as this was the first robot with fully functional joints. One of the key challenges we tried to address was the significant torque at the shoulder joint (circa. 4.5Nm) that necessitated four redesigns of key parts of the joint to ensure sufficient robustness.

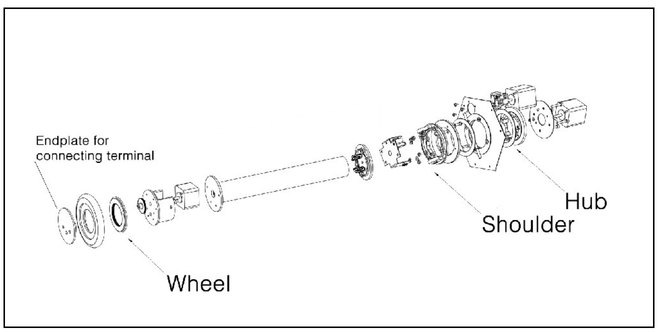

Figure 5. Robot's (version 2) Leg assembly

From Version 2, we have modelled the module using SolidWorks, and translated these files into formats compatible with our in-house 3D printing facilities (as illustrated in figure 5).

We relied on rapid prototyping 3D printers for the in-house production of most parts of the second prototype. The shoulder joint was however made of laser cut 1mm mild steel, the hub plates of laser cut acrylic, and the gear arrangements made of a combination of commercially available spur, bevel and pinion gears. We have used Oilite bearing for the shoulder joint and layers of OHP paper with lubricant as bearing at the hub and wheel joints.

Some of the 3D printed parts lacked structural integrity and had to be redesigned with increased thickness. This was notably the case of the shoulder joint motor mount (shown in figure 6(l)).

So far we have produced one single module of Version two and we have moved to the design of a new version bearing in mind the intended combinations of modules (as described in the next sections).

Figure 6. Prototype 2 details of the Hub & Shoulder joints (l), and wheel joint (r).

For the overall control of the robot, we have selected Arduino boards. These generated instruction to a stepper motor controller L297 in full step mode. The L297 generates a phase drive signal for the two phase bipolar step motors. In our configuration the motors were driven in half-step. The TTL logic level signal generated is then fed to a L298, a dual full H bridge driver. The signal coming out of the L298 is fed into our stepper motors (respectively 17HS-020E Mk 2 for the wheel, and 17HS-240E for the shoulder and hub joints).

The assembly of two modules requires the connection of two connecting terminals, one from each of the modules. We rely on an alignment and connection control algorithms. First, the two connecting terminals, located at the end-plates of each wheel, that are to be engaged, are moved nearer to each other by the overall motion of the modules. While one module takes the role of front half of the combination, the other module takes the role of the back half. Once the connecting wheels are sufficiently close, both modules stop moving and only the connecting wheels are controlled for fine movements. We rely, then, on an alignment control circuit, based on the comparison of IR photodiodes inputs at the back module, sensing LED IR signal outputs from the front module. We have conducted a successful demonstration of this circuitry. In our design, the LED and photodiodes are alternatively arranged on the connecting terminals. The resulting signals from the photodiodes are subtracted, then processed for gain and offset and used for control of the connecting wheel of the back module.

Once the alignment is achieved, a slight decrease of the shoulder angle at the connecting leg of the bottom module ensures contact between the two connecting terminals. The alignment of grooved pins and the chamfered holes at the top and bottom modules' connecting terminals ensure the stability of the connection thanks to power to release, semi-permanent magnetised latches. Further algorithms, to control the robot, were or are being developed and are listed in the appendix.

V. Combining Modules

The proposed combination of two PetRo modules is in our opinion, the most promising combination as it delivers a dog-like configuration, ensuring not only high mobility but also pet-like appearance. This configuration is made possible by connecting two modules via any of their wheel endplate's connecting terminals. Figure 7 shows the concept assembly as intended.

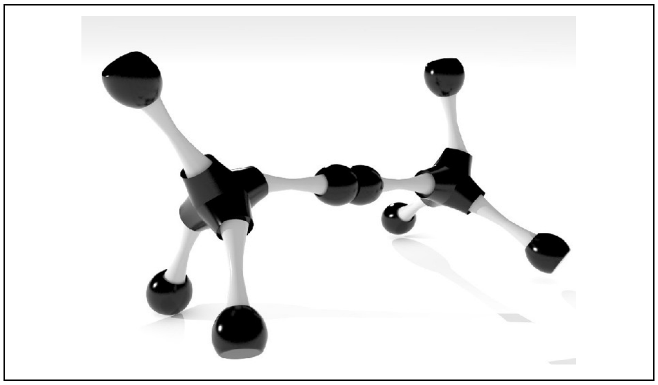

Figure 7. Dog configuration (front to the left)

One can immediately recognise the similarity to a dog and thanks to gait and movements, recognise where the forelegs and the head of the 'dog' are, comparatively to the hind legs and the tail.

A. Combination of several modules

More complex combinations of modules are possible, notably four modules that make up a 'spider' and as illustrated in Figure 8, five modules that can make up a 'caterpillar'. The main benefits of this later configuration is the resulting high mobility regardless of terrain conditions.

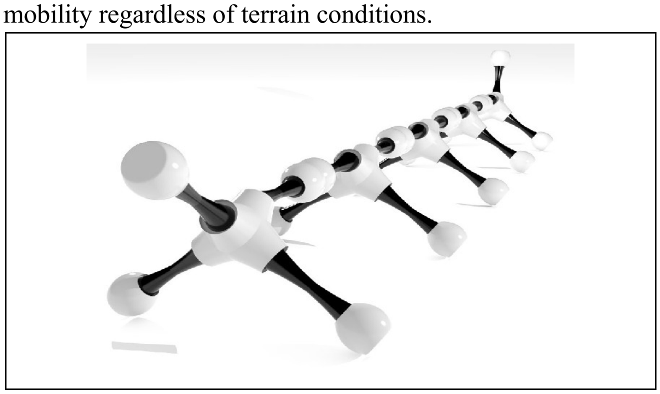

Figure 8. Caterpillar configuration (front to the left)

Other combinations are possible, and a larger number of modules results in a configuration that potentially offers higher mobility and specialisation. However, this comes at processing and control costs.

B. Mobility & Gait of combination of two modules

Mobility and gait of combination of modules increase significantly compared to an isolated module. In the case of two modules - what we call the 'dog' configuration - the mobility of the assembly is sufficient for most scenarios and theatres of operation. The gait of the assembly is that of a dog, with possible addition of the gait of other animals (see table II). However, the settings should consider if the assembly is to play the role of a pet and select the gaits accordingly. In which case, there should be limitations to what is possible, to keep the appearance of a pet consistent and convincing.

In this context, Table II shows the different gaits possible in a combination of two modules. In this table, L: left, R; right, F: foreleg, H: Hind leg, : ▲: lift off the ground forward, ▼: drop to the ground forward, ↻: bend horizontally clockwise from a top view with head to the left, ↺: bend horizontally anti-clockwise from a top view with head to the left. ( ): simultaneously, ▷: next step, ▷▷: repeat sequence. All gaits are inspired from animals, apart from the drive mode where the assembly behaves as if it were a car on four wheel drive.

TABLE II. MOBILITY OF COMBINATION OF TWO MODULES

Gait	Chronology	Inspiration
Drive	(LF,LH,RF,RH wheel drive)	Car [a]
Pace	(LF,LH)▲▼ ▷ (RF,RH)▲▼▷▷	Dog
Walk	LH▲▼ ▷ LF ▲▼ ▷ RH ▲▼ ▷ RF ▲▼▷▷	Horse
Diagonal Walk	RF▲▼ ▷ Trunk ↺ LH▲▼ ▷ LF▲▼ ▷ Trunk ↻ ▷ RH▲▼ ▷▷	Lizard
Trot	(LH ,RH)▲▼ ▷ (LF, RH)▲▼▷▷	Horse
Canter	RH▼(LH,LF,RF)▲ ▷ (LH,RF)▼ ▷ LF▼ RH▲▷(LH,LF)▲ ▷ LF▲▷▷	Dog & Horse

a. for non-pet applications

VI. PET-LIKE LANGUAGE

The bi-modular configuration, yields a dog-like appearance, we have therefore inspired the body language and expressions from dogs' propensity to express themselves so effectively through a variety of body movements. We have inspired the language from the actual postures dogs adopt to express what owners identify as emotional expressions. We see this language as an integral part of the interaction between the user and his/her robot. A means to provide feedback to the user that is intuitive, natural and can potentially reinforce an empathic connection between user and robot, in an analogy to the pet-owner relationship. In our vision, we see this language not just as a tool for communication per se, but as a reinforcement channel that emphasises certain messages to the user.

We have set up a language, described in table III, that allows for the communication of not only information in relation to the robot, but also to the task at hand and to the user. In relation to the robot, information is about issues such as power supply and system failure. When related to the task at hand the robot can communicate navigation and function issues. Finally the robot can also render positive and negative reinforcement in relation to its owner. A good example would be the need for him/her to exercise and the robot would behave as if in need for a walk in the park.

In the proposed language, there are two types of communication. The extrovert type, which is user-centric, focuses on either providing feedback based on relation to the pet-owner link, or about user behaviour that is in need of reinforcement. The introvert type, is about communicating the status and state of the robot in relation to power supply, system and function performance.

TABLE III. A PET-LIKE LANGUAGE

Name	Type	Purpose
Happiness	Extrovert	Positive reinforcement over short term
Fear	Introvert Extrovert	Task status indication Navigation problem
Sadness	Introvert Extrovert	System status indication Negative reinforcement
Anger	Extrovert	Negative reinforcement
Disgust	Introvert	Functional problem
Love	Extrovert	Positive reinforcement over long term
Relaxed	Extrovert	Idle state
Sleepy	Introvert	Power Supply issue
Flat	Introvert	System failure

An overview of the algorithm associated with the expression of the language is presented in the appendix. Figure 9 shows some examples of the language we have defined accordingly - It should be perceived and understood as a language that express various 'emotions' and 'moods' of the robot. The selection of what to express was dictated by two constraints: First, what a pet is likely to express and second, what can be achieved with PetRo design. In practice, in a bi- modular configuration, one can consider a module as forward and to be the shoulder of the dog with the forelegs and the head. The other module is therefore considered as backwards and includes the rump, the hind legs and the tail. The rendering of the language is the relative arrangement of all these parts. The angle between the forelegs, the height of the head, the head shakes, the inclination of the trunk, the height of the tail, the wagging of the tail, and finally the angle between the hind legs. In combination, these various arrangements were sufficient to deliver a language that is closely related to and recognisable as the expressions of a pet.

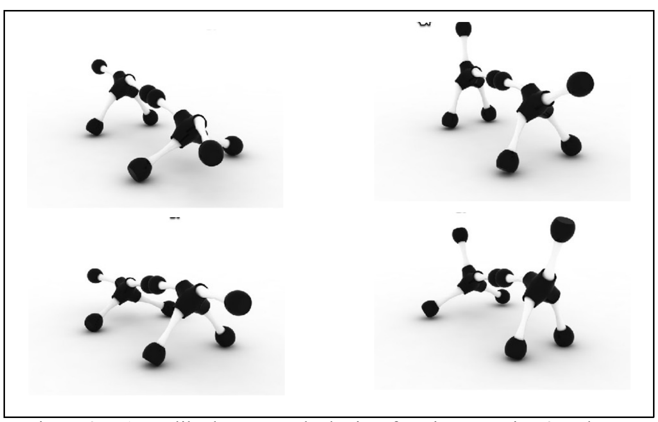

Figure 9. A pet-like language clockwise: fear, joy, surprise & sadness (considering the front of the pet to the right, and the back to the left)

One of the main drawbacks of the omni-directionality is the inherent lack of orientation. Although a body with direction allows for postures that are expressive, it is less so in the case of PetRo's design. Hence the need for body movements to render emotions, as these immediately give a sense of direction to the robot's body and facilitate the perception of a pet.

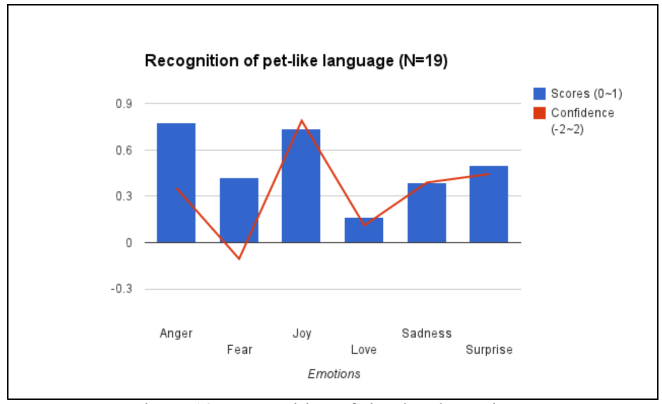

Figure 10. Recognition of simulated emotions.

To evaluate the effectiveness of the language selected we have presented animations on a computer display of the various emotions to test subjects (N=19, Undergraduate students from the School of Design, 4 Female, 15 Males). The emotions were presented in a sequence of pseudo-random order. Participants were given a questionnaire to answer, which included the Emotions to be recognised after each animation, along a bipolar scaled rating of their confidence level (Not at all -2~ Very Confident+2), The results of their scoring of each emotions is presented along the confidence levels they had in their answers in Figure 10. The emotions that are most recognised correctly are Anger (Score 0.777, Confidence 0.3529) and Joy (S. 0.736, C. 0.789). Then in decreasing order, Surprise (S. 0.500, C. 0.444), Fear (0.421, C. -0.105), Sadness (S. 0.388, C. 0.388). Finally the least recognised emotion was Love (S. 0.166, C. 0.111). The only emotion with a negative confidence as reported is Fear, indicating that improvements are clearly necessary to make the expression of the emotion much clearer.

VII. POTENTIAL APPLICATIONS

We are considering two types of applications. As a pet the robot provides physical and emotional benefits for its owner/user. As with real pets, there is the potential to stimulate owners, by requiring from them care, exercise, and attention. If the emotions expressed by the robot are effective at triggering empathy, they will help owners to cope with emotional distress. In the context of an elderly owner, this is particularly beneficial.

Furthermore, PetRo has none of the drawbacks of a real animal, such as allergy risks, misbehaviours and hygiene issues. While not a replacement for a real pet, it should nonetheless become a possible alternative.

The second type of application we are considering are those that take full advantage of the key features of the design, i.e. omni-directionality, modularity and self-assembly. One particularly salient application is that of search and rescue when the theatre of operation cannot, in most cases, be foreseen. Several modules can be thrown into the scene and guided as to the best configuration to adopt to perform inspection of buildings and the search for survivors.

VIII. Future Work

To increase mobility, for the next version of PetRo (V3), we have selected omni-directional wheels as well as better manufactured parts, that have increased structural integrity and strength. There is also a significant improvement in the power transmission from the motor by adding gearboxes for each of the motors with ration of 24:1 (IP43 gear head). Another issue that we have not attempted to resolve is the issue of power supply: The current version is tethered to PSUs. Future works include the design of battery enclosures, terminals for power distribution amongst modules, and a data bus for distributed processing and control of the assembly's sensor data, actuators and mission performance. Connecting terminals will be present at the end of each wheel, they will possess doubled set of paired connecting pins and holes, as well as power and data connectors. Finally, sensors will distributed in tripled sets around the robot's hub, in an arrangement that allows for interchangeability, should the need arise.

IX. Conclusion

PetRo as a homogeneous modular robot has been designed with many redundancies in its design, control and electrical circuits, to ensure reliability and resilience to a variety of theatres of operation: A pet is not expected to only operate over a smooth horizontal surface. An expressive language has also been designed, to increase the likelihood of the robot being used as a pet. We purposely limited the language to a small set to reduce possible confusion in user interpretation and to keep the interaction simple and easy to learn. We have now reached a stage where we are confident in the feasibility of the concept and are working on the third version of the robot. In this version, comprehensive user tests will, hopefully, vindicate the design decisions we have made so far.

Appendix

We have developed several algorithms for the controls and functions of the robot. Table IV gives a general summary.

TABLE IV. PetRo Algorithms

Name	Purpose
Orientation	Determine the up and down of a module, relying on an array of 12 tilt switches distributed around the hub
Posture	Determine current orientation and angle of each of a module joints, relying on encoder and step counters on each joint
Velocity	Estimation of velocity by deduction from posture and encoders at moving joints (depending on gait)
Language[a]	Adoption of body posture according to language
Detection[ab]	Detection of other modules within vicinity thanks to 12 ultrasound emitter/sensors on hub
Alignment[ab]	Alignment of connecting legs thanks to ultrasound emitter/sensors on hub and IR emitter/sensors on wheel's endplate
Connection[b]	Connecting plates fine alignment thanks to IR emitter/sensors. Completed with a locking of endplates.

a. under development, b. for self-assembly

For the expression of the language, an algorithm (shown in Figure 11) has been developed, taking into account both internal and external information available, as well as previous and current states of the robot.

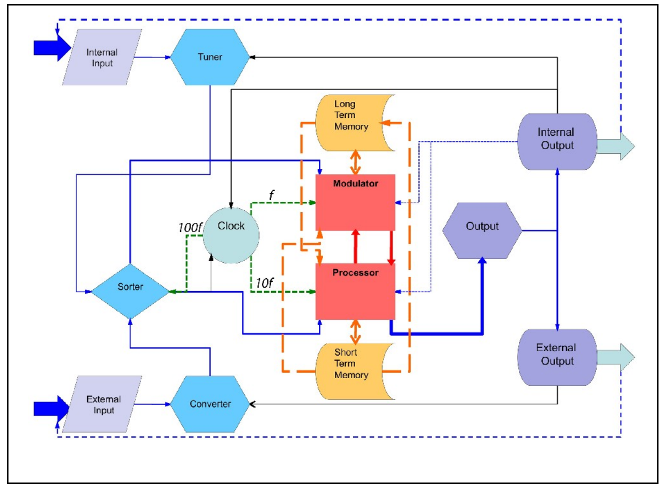

Figure 11. Overview of language algorithm

Acknowledgment

Thanks should be given to the students that have helped with the various versions of PetRo. Niek GROENENDAAL for the first prototype, Tom NAPPEY, Ross LAWTON, Josh HORNBY for the second prototype. James THOMAS and Simon SCOTT-HARDEN have also made contributions to the second prototype.

Photo in figure one is from John KERGUELEN, used with kind permission.

References

[1] T.Fukuda, Y. Kawauchi, “Cellular robotic system (CEBOT) as one of the realization of self-organizing intelligent universal manipulator” in *Proc. 1990 IEEE Int. Conf. on Robotics and Automation*, Cincinnati, OH, USA, vol. 1, pp. 662-667.

[2] M. Yim, “New locomotion gaits” in *Proc. 1994 IEEE Int. Conf. on Robotics and Automation*, San Diego, CA, USA, vol. 3, pp. 2508-2514.

[3] M.Yim, D.G. Duff, K.D. Roufas, “PolyBot: a modular reconfigurable robot” in *Proc. 2000 IEEE Int. Conf. On Robotics and Automation,* San Francisco, CA, USA, pp. 514-520.

[4] A. Castano, S. Wei-Min, P. Will, “CONRO: towards deployable robots with inter-robots metaphoric capabilities” *Autonomous Robots*, vol. 8, no. 3, pp. 309-324, 2000.

[5] G. Aloupis, S. Collette, M. Damian, E.D. Demaine, “Realistic reconfiguration of crystalline (and telecube) robots” *Algorithms Foundation of Robotics VIII,* Berlin:Springer, 2009, pp. 433-447.

[6] L. Xuan, Z. Minglu, L. Wei, “Methods to modular robot design” in Proc. 2008 IEEE Intl. Symposium on Intel. Info. Tech. Application, pp. 663-

[7] S.Popesku, E. Meister, F. Schlachter, P. Levi, “Active wheel – An autonomous modular robot” in Proc. 2013 IEEE Robotics, Automation and Mechatronics, pp. 97-102.

[8] B. Salem, “Development of PetRo: a modular robot for pet-like applications” in *Proc. Sensor Fusion and Decentralised Control in Robotic Systems IV, par of Int. Symposium on Intelligent Systems and Advanced Manufacturing, SPIE Photonics East*, Boston, MA, USA, pp. 170-177.