LocoKit: A Robot Construction Kit for Studying and Developing Functional Morphologies

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Abstract. We describe a robot construction kit named LocoKit and a method for studying functional morphologies. LocoKit consists of simple mechanical parts that allow for construction of a wide range of morphologies and modular electronics for instrumentation and control. The method relies on LocoKit for constructing functional morphologies and an experimental setup borrowed from the study of functional morphology in animals. We demonstrate the use of LocoKit and the method in a case study on quadruped locomotion and conclude that the methodology represents a systematic and efficient approach to the study and development of functional robot morphologies.

Keywords: Robot construction kit, experimental methodology, functional morphology

1 The Role of Functional Morphologies in Robotics

There is a potential to increase the adaptability, robustness and energy efficiency of robots, while decreasing their complexity and cost, by adapting the function of their morphology to support their desired behaviors[1]. Unfortunately, it is not clear how to perform this morphological adaptation systematically and efficiently. In an attempt to address this problem, we propose an iterative, bottom-up, and model-free methodology that relies on a robot construction kit named LocoKit, shown in Figure 6, and an experimental setup borrowed from the study of functional morphology in animals.

Our methodology is based on the assumption that a robot's behavior is a result of the interaction between its morphology, control, and environment[1]. It is also based on the assumption that, for robots with non-trivial morphologies, this interaction is so complex that modeling is intractable and thus our methodology is in line with one of the tenets of behavior-based robotics, namely, that *the world is its own best model* [2]. A consequence of this is that to we have to rely on a tedious trial-and-error process to develop a useful combination of morphology and control for a given environment. Our first proposal is to use a robot construction kit to make the development process more efficient. A robot construction kit allows us to rapidly explore a morphological space without the need at every iteration to make mechatronics from scratch, for instance, in a study related to the case study on locomotion we will present in Section 5, we were able to build and do experiments with 51 variations of the same morphology in one day. The second proposal is to use an experimental setup typically used in the study of functional morphology in animals. Basically, the experimental setup provides data that is much richer than what is typically seen in robotics. An experimental setup may for instance provide motor control outputs synchronized with high-speed video, three-dimensional motion capture of key points on the morphology (allowing for calculation of relative position, speed, and acceleration), and with output of transducers both internal and external registering mechanical variables (e.g. forces, velocity, acceleration, pressure, etc.). This rich data allows us to measure overall performance parameters like speed and energy consumption and, in addition, how specific elements of the morphology or controller contribute to the whole. This giving us valuable data to systematically understand and improve both morphology and control. It is our hope that the methodology described here with its focus on experimental methodology and the use of LocoKit may provide a way to increase our understanding of the role of functional morphologies. In addition to making it practical to take advantage of functional morphologies in robots.

In the following, we will briefly describe related work, the methodology, the implementation of the LocoKit robot construction kit, the experimental setup, and a case-study demonstration on robot locomotion demonstrating the methodology in practice.

2 Related Work

We will limit our review of related work to methodologies that consider the morphology of the robot important. An approach inspired by artificial life is to evolve morphology and behavior in simulation [3] and then transfer the result to the real world either through three-dimensional printing [4] or by using modular robots [5]. However, both methods are limited by the intrinsic limitations of how complex interactions can be simulated. Another similar approach is to use a mechanical system whose configuration can be changed and use this as a basis for evolution of morphology in the real world [6].

Our approach is also related to the bio-inspired approaches where animal morphology inspires robot morphology, e.g., [7]. In particular, the work that puts a strong emphasis on experimental analysis and validation [8, 9]. However, in contrast to this work, we use the experimental data as a design tool and not only for analysis and validation.

LocoKit originated in the field of modular robots [10, 11], but is more similar to construction toys such as Meccano and LEGO Mindstorms. In contrast to the toys, LocoKit is more geared towards building sensor-and-actuator-rich, dynamic robots with flexible morphologies. The contribution of this paper is an extended description of our methodology compared to previous work [12] and the introduction of LocoKit.

3 Methodology for Testing Morphological Hypotheses

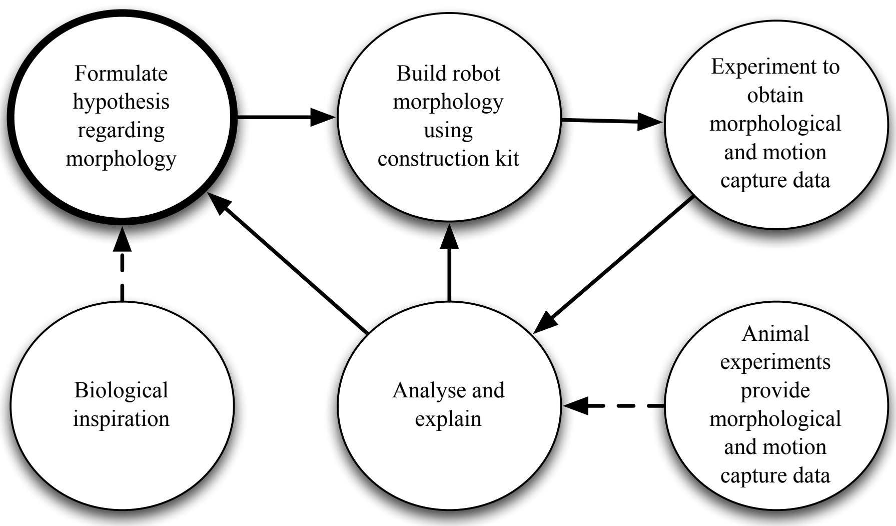


Fig. 1: Methodology for testing hypotheses regarding functional morphology (see main text for explanation).

The methodology we propose is outlined in Figure 1. The methodology is hypothesis-driven so the first task is to formulate a hypothesis regarding functional morphology. This hypothesis may have a biological origin, but this is not crucial. The second step is to build a robot using a construction kit to test the hypothesis. The construction of this first robot is guided by intuition and experience, however, as we will see errors or bad designs may be discovered and corrected in later iterations. Once the robot has been constructed, relevant morphological and motion data are measured. What to measure was outlined in the introduction and will be elaborated in the section on experimental setup later. This rich data provide the background for analyzing and explaining the function of the morphology. It is an advantage if it is possible to obtain measurements in a form that is comparable to that of other morphologies, biological or artificial, because that makes it possible to do a comparative analysis. This helps not only in analysing the data, but also in explaining the functionality of the morphology. Undesired functionality can often be tracked to mechanical or control problems in the robot design which then can be fixed in another iteration. Once the function of the morphology is acceptable from a technical point of view, the measured data can be used to support or reject the scientific hypothesis or, as is often the case, be used to refine the hypothesis.

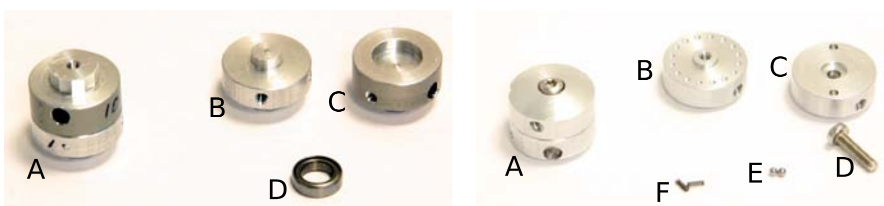
The methodology is based on an experimental methodology that is common to all of science. The methodology is, however, optimized for the study of functional morphology. In particular, we suggest to use a robot construction kit and an experimental setup borrowed from biomechanics.

4 LocoKit Implementation

4.1 Mechanical Components

The LocoKit elements connect with 4mm, off-the-shelf rods of varying lengths. We use two types of rods either carbon-fibre or fibre-glass enhanced plastic rods, but other materials are available as well. All of the construction elements of LocoKit can be connected to or mounted on these rods using one or more set screws. In the following four sections we will describe the four groups of mechanical components.

Structural Components All morphological structures built from LocoKit are built from the rods described above and two mechanical connectors, a fixed joint and a rotary joint, both made in aluminium.



(a) Rotary joint (A). Left part of joint (B). Right part of joint (C). Bearing between right and left sides (D). The two sides are glued onto the bearing.

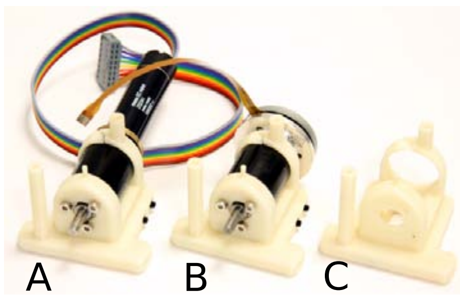
(b) Fixed joint (A). Left part of joint (B). Right part of joint (C). Mounting bolt (D). Balls (E). Springs pushing the spheres towards opposite side (F).

Fig. 2: LocoKit joints

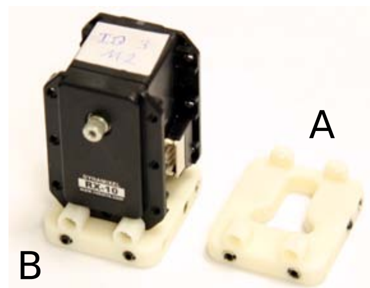
The rotary joint, shown in Figure 2a, is used to connect two rods and allows the rods to rotate freely in parallel planes. On the sides of the rotary joint there are mounting points that allow for future, additional elements to be attached.

In Figure 2b the fixed joint is shown. This joint can, like the rotary joint, connect two rods, but in contrast to the rotary joint, it can fix the angle between them. The joint rotates freely initially, but provide tactile feedback at one of 12 evenly distributed angles due to the spring-load steel ball and the 12 matching holes on opposite sides of the joint. If the position is to stay fixed inside or outside the 12 preferred angles the outside screw can be fastened. This arrangement allows for rapid, precise construction of commonly used construction elements such as rectangles, triangles, etc., but leave the user free to use an arbitrary angle if needed.

Motor Mounts In LocoKit we currently use three types of motors and two motor mounts since two of the motors use the same type of mount. Despite being different, the two mounts are designed to be interchangeable without changing the mechanical structure to which it is attached. We currently support Dynamixel Rx-10 motors, which together with its mount is shown in Figure 3b, and Maxon motors with a 22mm gearing, two of which are shown attached to their mount in Figure 3a.



(a) Maxon motor mount (C), mounted with a 40W motor (A), and a 6W motor (B).



(b) Dynamixel motor mount (A) with motor mounted (B).

Fig. 3: LocoKit motor mounts.

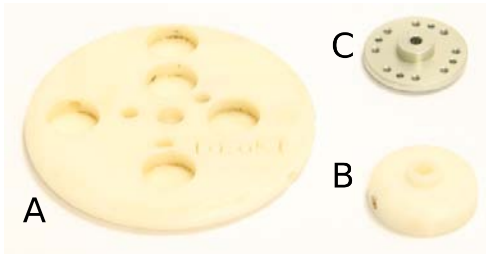
Transmission Components In Figure 4a we see the components used to transfer the torque from a motor to the connection disk (A). The design includes two converter disks, (C) and (B), which allow us to transfer torque from both Maxon and Dynamixel motors. The connection disk has five holes at different distance to the center which provides the attached rod rotation with different offsets.

In Figure 4b is shown the components we use to attach a rod to a connection disk. The assortment of pieces allow us to mount a rod that rotates freely in a plane parallel to the connection disk and allow us to make connections that are compliant in the direction of the rod.

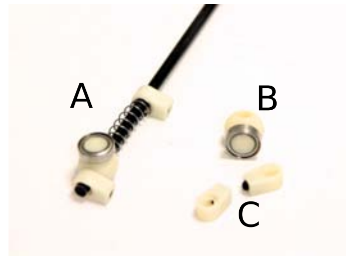
Miscellaneous elements In addition to the core elements presented so far, we also have a range of feet elements to be mounted at the end of a rod ranging from simple ball-feet to spring-load compliant feet. We also have elements for mounting batteries and power, control, and motor electronics boards, which we will describe below, to the frame of the robot.

4.2 Electronics

LocoKit electronics provide internal and external communication, processing, a sensor interface, low-level control of actuators, and a power supply for electronics as well as actuators. These functionalities have been distributed across three



(a) (A) Connection disk. (C) and (B) Converter disks allowing us to use different motors on the same connection disk.



(b) (A) A rod compliantly attached to the connection disk. (B) Pieces that connect a rod to a connection disk.

Fig. 4: LocoKit transmission components.

boards: power, processing and communication, and motor control. The processing and communication board also hosts the sensor interface. This design makes it easy to extend LocoKit with new boards, for instance for new types of actuators. It is also relatively easy to replace one of the existing boards with an improved version at a later stage.

For communication internally between the processor and the motor controller boards we use a full-duplex RS-485 bus operating at 1Mbps. In order to reduce the amount of wires the communication is wired through a connector which also distributes power.

Power board The power board provides a stable 24V voltage at a continuous current of up to 10A with an efficiency between 90-95% (a result based on experiments). The power board provides 240W, which is considered more than sufficient, while keeping weight to a minimum. We use lithium polymer batteries due to their high power to weight ratio. We use 6 cells in series giving a voltage of 18-25.2V. We have a battery pack that weighs 450g with a capacity of 2650mAh and another weighing 100g with a capacity of 600mAh for smaller robots. The power board also provides protection for the batteries.

Processor and communication board The main purpose of the processor board is to provide a computational platform for control applications and data logging, a wireless interface to a PC and an interface to sensors. We use the commercially available Gumstix Overo Air board which includes: A 600MHz TI OMAP3 processor, 512MB of RAM, Wifi, Bluetooth and an microSD card reader. The use of Gumstix enable us to use Linux as the operating system for LocoKit, enabling us to use many standard software packages directly. Currently, we are using the Angstrom Linux distribution which is targeted at embedded systems. The Gumstix board is mounted on an interface board, which together make the processor and communication board. The interface board provides various functions and interfaces: low voltage regulation, three push buttons, 5 LEDs, 8 general purpose digital I/O, 4 analog inputs, an I^2C interface, an RS-485 interface, and finally a USB device port for debugging.

Motor controller boards Each motor in the robot is controlled by a separate board, these boards implement the low-level motor control algorithms and the power electronics needed to operate the motors. The motor controller boards are implemented using a small 48MHz ARM7 processor which performs both RS-485 communication with the processing and communication board and low-level motor control. The motor is driven by a standard triple half-bridge. Besides the essential functionality a simple sensor interface is provided consisting of four pins which can be configured as digital inputs or outputs or as analog inputs. The physical connectors are compatible with most hall sensor based brushless DC motors from Maxon.

5 Case Study

In our case-study we will demonstrate the use of our methodology and LocoKit in practice. We will focus on the question of how the morphology of the robot influences locomotion. Specifically, how compliant feet influence the robots ability to walk.

5.1 Experimental Setup

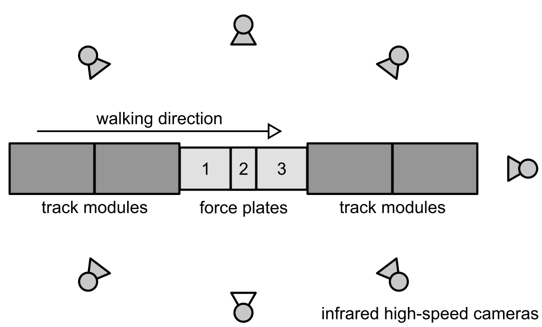


Fig. 5: The experimental setup consisting of three force plates and seven infrared cameras for motion capture. The camera with a white cap also recorded video.

The experimental setup is shown in Figure 5. The track consists of three force plates[1] organized in a row with two wooden tracks at both ends. Between

[1] Two 60cm x 50cm, Type 9260AA6; one 30cm x 50cm, Type 9260AA3, Kistler, Winterthur, Switzerland

two 60cm x 50cm force plates the smaller 30cm x 50cm force plate was installed. The force plates as well as the track modules were covered with carpet. For motion capturing 7 infrared high-speed cameras[2] were installed around the track operating at 250Hz. One camera was, in addition to automatic motion capturing, recording high-speed video of the robot.

5.2 SpringyBot Hypothesis

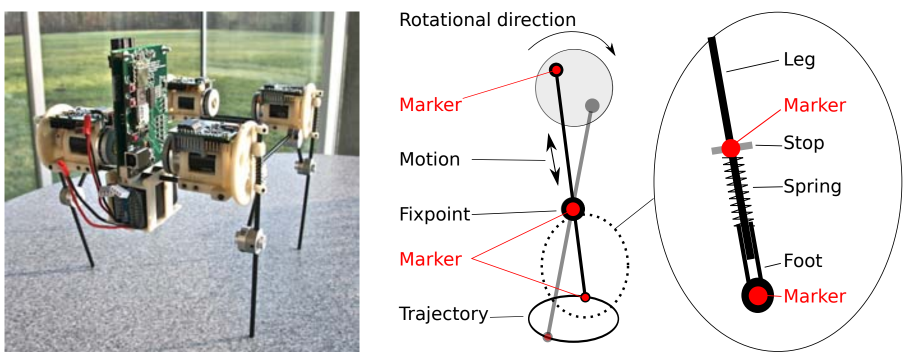


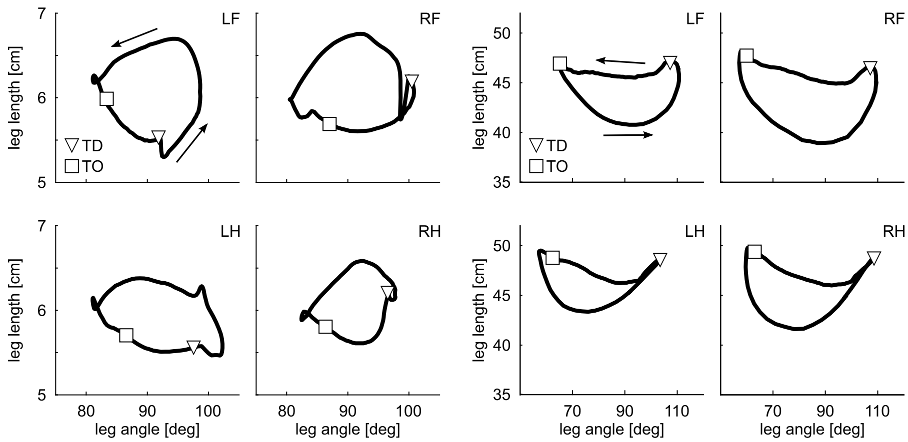
Fig. 6: The SpringyBot built from LocoKit and a schematic of its leg design. The leg is driven by the top disk and generates the trajectory shown. To be able to track key parts of the morphology infrared markers (red) have been placed at the positions shown.

We use LocoKit to construct the robot, named SpringyBot, shown in Figure 6. The leg design has been inspired by concepts found in Scout [13] and iSprawl [14]. In Figure 6, a sketch shows how the legs of SpringyBot works. The continuous rotation of the connection disk at the top of the leg creates a foot trajectory as shown. The foot contains a spring which we hypothesize can keep the center-of-mass of the robot at a constant height as seen in a Spring Loaded Inverted Pendulum (SLIP) model [15].

5.3 Experiments

In our experiments we had the robot walking using a slow trot gait on the test track while being monitored by the cameras as shown in Figure 5. We divided the resulting data into gait cycles and extracted the total length of the leg, the leg's angle with respect to the ground, and the length of the compressible part of the leg (due to the spring). From this we also calculated the incompressible part of the leg for completeness.

[2] Oqus series, Qualisys, Gothenburg, Sweden



(a) Phase plot for trotting SpringyBot (b) Phase plot for trotting dog.

Fig. 7: Phase plot for each leg (L - left, R - right, F - front, H - hind, e.g. LF - left front leg) showing the length of the leg as a function of specific angle for SpringyBot and a trotting dog (▽: Touch down, □: Take off)

Figure 7 shows phase plots of the total leg length as a function of leg angle for SpringyBot and for comparison a trotting dog. The discontinuity of the phase plots of SpringyBot is due to the spring since it is the only element of the leg morphology that can change rapidly. What can be seen from the phase plots, most clearly from the top-left one, is that just after contact with the ground and just before take-off the leg is shortened and lengthened, respectively. In the alternative visualization of the data in Figure 8, it becomes clear that it is the spring that on contact with the ground immediately compresses fully, and shortly before takeoff extends fully again and thus is compressed during most of the stance phase. In other words, the spring works like a shock absorber. This could be a desirable function of the morphology, but our goal was that the spring should shorten the leg during mid-stance to keep the center-of-mass at the same height similar to that of the SLIP model and the function of the dog leg. The implication for us then is that the spring is too short or perhaps too weak to support the weight of the robot and as a consequence we will in the next iteration try with first a longer and then a stronger spring. Another interesting research direction that this data indicates is to study the use of two springs, one for absorbing the initial impact and one for stabilizing the center-of-mass.

6 Discussion

The specific problem or solution is not important here. The point is that discovering the problem or even realizing it without the use of the rich experimental

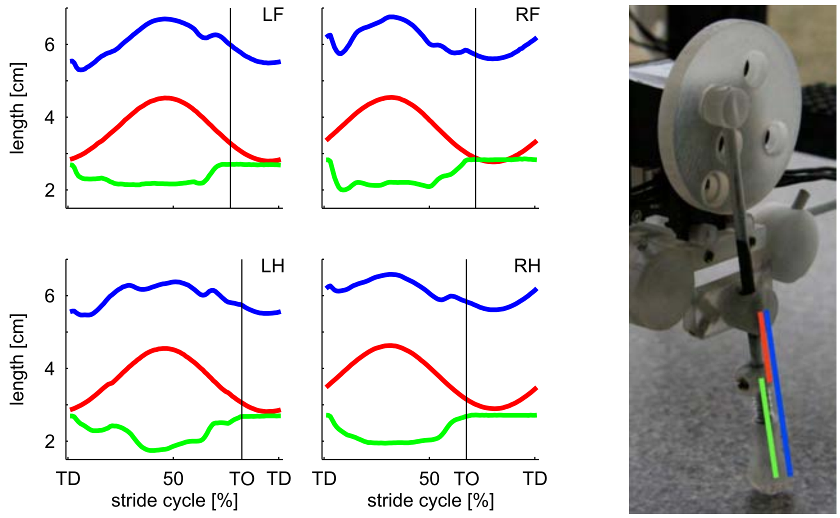


Fig. 8: Shows the length of different segments of the four legs during a stride cycle (colors refer to the photo on the right, and L - left, R - right, F - front, H - hind, e.g. LF - left front leg). The green curve represents the compressible part of the leg and shows how the spring is fully compressed during almost the entire stance phase.

data would have been difficult because of the robot's dynamic behavior. A problem that will only be aggravated as we move towards faster locomotion. A second point is that the data is recorded in a way that makes it directly comparable to animal data which also can be an aid in debugging morphological problems. Finally, since the robot is built from LocoKit we can rebuild the robot quickly and perform yet another experiment and thus rapidly converge towards the desired functionality.

At a more general level, the case study demonstrates how we use our experimental methodology in practice in the context of understanding the role of morphology in locomotion. A crucial point about this case study and our research method in general is that experimental data is absolutely crucial. Experimental data represents the true function of the morphology taking all constraints of the environment into account and thus is a valuable design tool which in contrast to many other approaches may, if succesful, provide us with a functional robot at the end.

Modeling is not employed at this stage, but may be useful after the robot has been developed, for instance as a basis for simulation or comparison with similar robots. In other words, models are useful for analysis and comparison, but we think that experimental data is more valuable as a design tool for designing functional morphologies.

7 Summary

It is a significant challenge to understand and, for roboticists, take advantage of functional morphologies. In order to address this challenge, we introduced the LocoKit robot construction kit that allows for rapid exploration of a morphological space. LocoKit, together with an experimental setup borrowed from biology, also plays a crucial role in the proposed iterative, bottom-up, model-free method for the study of functional morphology in robots. We finally presented a case study showing how LocoKit and the methodology can be used in practice for the study of functional morphology in the context of locomotion. We conclude that LocoKit combined with our methodology allows for systematic and efficienct development and understanding of functional morphologies. As a whole, we hope that our contribution can aid in the understanding of and development of more morphologically advanced robots.

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