DESIGN OF PASSIVE DYNAMIC WALKING ROBOTS FOR ADDITIVE MANUFACTURE

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Abstract

Ongoing research in the direction of printable, non-assembly mechatronic systems give rise to the need for multi-material printing, including electronics. However, there are robotic systems that do not use electronic components and still exhibit complex dynamic behavior. Such passive dynamic systems have the potential to save energy and component cost in the field of robotics compared to actuated systems. Ongoing research in computational design synthesis of passive dynamic systems aims at automatically generating robotic configurations based on a given task. However, an automated design-to-fabrication process also requires a flexible fabrication method. Towards the goal of printing functional, non-assembly passive dynamic robots using Fused Deposition Modeling (FDM), this paper explores designing and fabricating passive walking robots and all necessary components using single material FDM. Two configurations of passive dynamic walkers are re-designed and fabricated in this paper. For one of them all components are printed in one job and only little assembly after printing is needed. However, the gait cycle of the second configuration is much more sensitive to small parametric changes and therefore more flexible prototyping is needed in order to allow adjusting of the robot after printing. Moreover, FDM printed robotic joints with sufficient smoothness and axial stiffness are required and a variety of different joint assemblies are designed and tested for the robot prototypes. Even though the most stable gait for the second robot is achieved using a metal bearing instead of the FDM printed ones, this is not necessary for the first robot example. The approach to prototyping with FDM presented in this paper allows achieving functionality through design iteration without incurring significant cost. To arrive at feasible solutions, a modular design approach allows to combine different joints, legs, feet and balancing weights and the connection points of the different elements are adjustable after printing, which makes it possible to shift the center of gravity and other variables of the robot.

Introduction

Additive Manufacturing (AM) can reduce post-processing cost by fabricating assemblies as monolithic parts in single processes. However, the technology to fabricate functional components, such as an actuated robotic system with integrated electronics, is still in its infancy. In contrast, passive dynamic systems do not require such components and are therefore suited for single-material AM processes. A passive walking robot, for instance, walks down a slope with gravitational force alone and without actuators. The design of a passive walking robot helps to understand the mechanics of human walking and it allows actuated, walking robots to be built with greater energy efficiency. First attempts to build passive dynamic walking robots started in 1990 [1]. Passive dynamic systems have, in general, the potential to save energy and component cost in the field of robotics compared to actuated systems. Ongoing research in computational design synthesis of passive dynamic systems aims at automatically generating robotic configurations based on a given task [2]. To extend this approach to an automated design-to-fabrication process choosing AM as fabrication method can offer a lot of flexibility.

The goal of this paper is to explore the potential of low cost FDM fabrication of passive dynamic walking robots. Based on existing passive walking robots, two suited configurations are chosen and redesigned to be fabricated using AM. Joints are the most complex parts and different joint designs are tested and compared. The passive walkers require joints with low friction as well as high axial stiffness. The more advanced of the two robots is built in a modular way, such that the single components can be replaced with different versions. In order to test the suitability of the parts, a variety of prototypes covering all components are built and the influence of the components on the gait of the passive walker are examined with the help of experiments. To achieve a stable gait, significant fine tuning is necessary, since this passive walker easily looses balance. A second, more robust configuration of a passive walker is built, which has a stable gait without requiring much balancing. The imprecision of 3D-printed components are less problematic for this configuration, due to less sensitive dynamics.

Background

The theory of passive walking has been studied extensively in literature. A mechanical model for passive dynamic walking can be described with the rimless wheel model [3] [4] and the more complex compass gait model [5] [6]. Analyses showing which parameters influence the gait of the passive walker and how they can affect the dynamics of the gait can be found in [7].

The most intuitive and straightforward passive walker is a configuration with two legs and no knees as shown in Figure 1a. This robot constructed by Tedrake is made from wooden and metal parts with a pin joint as the hip [6].

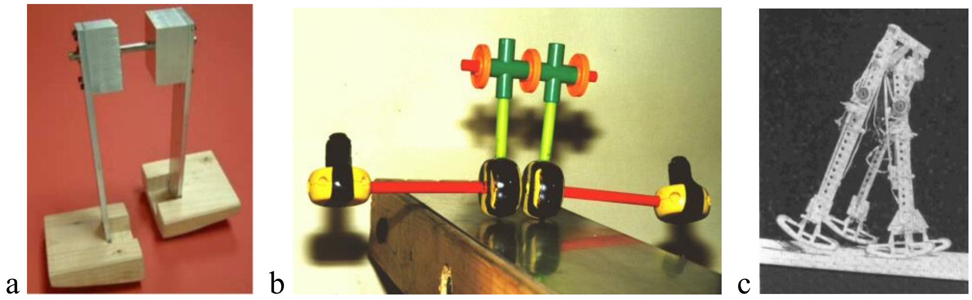


Figure 1: Passive Walkers. a: Tedrake [6]. b: Colman and Ruina [8]. c: McGeer [1].

Pushing the passive walker sideways lifts the opposite foot off the ground and thereby solves the problem of foot clearance. When placed on a slope, this opposite foot will swing forward due to gravity until it touches the ground again. The energy dissipation through friction and collision are overcome by gravitational forces. With experiments, Tedrake determined which curvature of the feet provides a stable gait on a small decline.

Colman and Ruina [8] built a passive walking robot with components from the Tinkertoy construction set, see Figure 1b. Contrary to Tedrake's construction, the Tinkertoy passive walker cannot stand. The Tinkertoy prototype exhibited a stable gait, although this is not achieved in simulations in [8] . Coleman and Ruina achieved a stable gait by changing the centers of mass of the legs.

The third passive walker shown in Figure 1c was developed by McGeer [1]. A knee joint is included in this prototype to solve the problem of foot clearance. The robots presented above solve this problem by tilting sideways. McGeer’s robot demands higher quality of the components due to its greater sensitivity and complexity.

A fourth configuration of a passive locomotion robot is shown in Figure 2. The kangaroo is able to “hop” down a slope without actuators. Similarly to McGeer's passive walker, the kangaroo has two permanently fixed outer legs. In between these legs, the kangaroo touches the ground with its upper limbs and tail. This causes a forward / backward motion of the body. While balanced on the upper limbs, the legs move forward and the cycle continues. The kangaroo has four contact points with the ground and is statically stable.

Figure 2: Hopping Walker has a robust gait [9].

Single-material AM has been used to fabricate non-assembly mechanical joints [10] as well as complete articulated toy characters [11]. Actuated deformable characters have been built using multi-material AM [12]. In [13] robots are automatically designed and the robot skeleton is fabricated using AM. With these approaches, however, additional external actuators are required.

To circumvent the need for the addition of electric parts, this paper demonstrates how low cost single-material FDM can be used to fabricate functional passive dynamic walking robots that do not require actuators. It investigates the possibility to use FDM fabricated parts only. In order to do so, extensive experimental testing and fine tuning of the printed walking robots is required. A variety of joints that can be printed with FDM are designed and tested, as well as compared with metal ball bearings.

Concept Design

From the existing passive walking robots presented, two suitable configurations are chosen for fabrication. The kangaroo is chosen because of its robust gate and the design from Colman and Ruina is chosen because of its low complexity and the configuration can be fine-tuned after printing by shifting the center of gravity to achieve a stable gait. While different feet curvatures, as used by Tedrake, could be easily fabricated using AM, they are not adjustable once printed and therefore Tedrakes configuration is not chosen.

The design presented in this paper is shown in Figure 3a. It consists of the feet, the legs, a hip joint, an extension element that allows shifting the center of mass in all three dimensions and balancing weights with different masses. Connection elements allow to fix and unfix the components, as well as shifting the connection points.

Figure 3b shows the geometric parameters that can be varied. b_1, b_2 and h_2 are the positions of the balance weights, h_1 is the height of the hip joint and w is the distance between the legs. Other important parameters are the curvature of the feet and the surface adhesion, as well as all the masses and moments of inertia of the feet, legs, connection elements and balance weights.

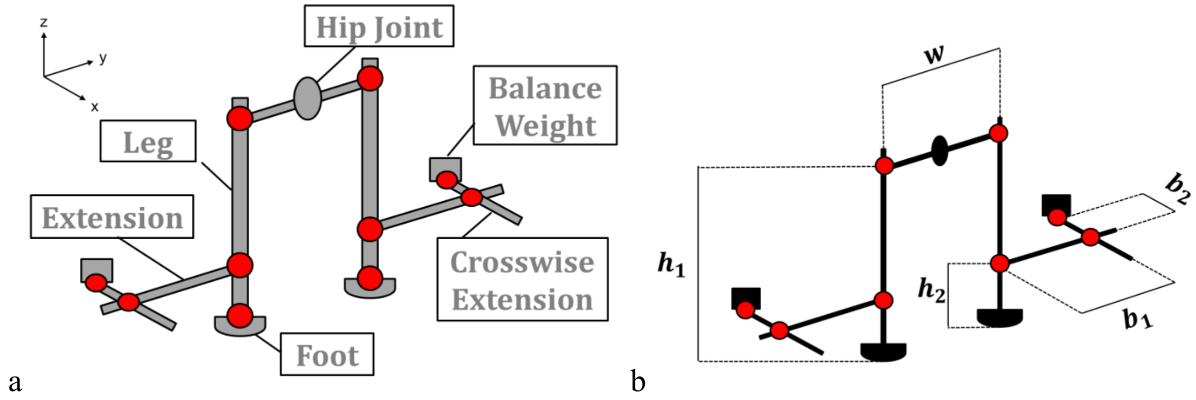


Figure 3: General Configuration

In addition to the passive walker presented in this section, which has only two contact points to the ground, a version of the kangaroo, shown in Figure 2, is redesigned for additive manufacturing. This configuration has four points that can be in contact with the ground and has a much more robust gate.

Component Design

In this section the components of the passive walker and their advantages and disadvantages in regard to the dynamics are presented. The components are designed and modelled using NX CAD software [14] and fabricated using a StrataSYS uPrint SE Plus printer. This FDM machine uses an ABSplus thermoplastic material and prints with a layer thickness of 0.254 mm [15].

Hip Joint

For the hip joint, different designs are tested. The main challenge for the 3D printed components is to achieve a constant low friction during rotation, which is obtained by increasing the clearance between the moving parts of the joint. On the other hand, a smaller clearance is desired for more axial rigidity.

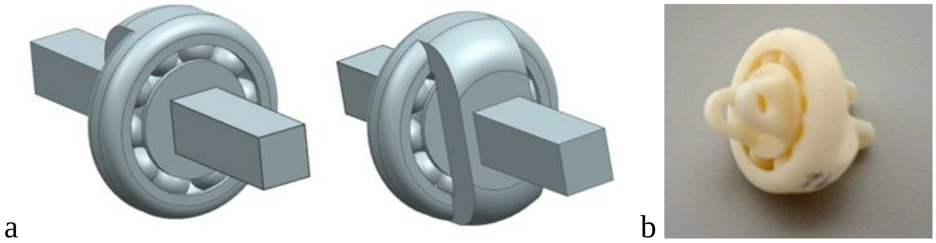


Figure 4: Bearing III. a: CAD model front- and back-view. b: Printed part

The first design is shown in Figure 4. This bearing exhibits a smooth spinning behavior with constant friction, but significant play on the center axis of the hip joint. Secondly, a planetary gear is considered (see Figure 5). Connecting one leg to the outer gear and the other leg to the inner gear results in a slight asymmetry in the moment of inertia of each leg. Moreover, the rigidity with respect to the center axis did not improve compared to the first bearing. Both bearings are printed with a range of different clearances between ball and casing and between gears of the planetary bearing, in order to find a balance between rotational smoothness and axial stiffness.

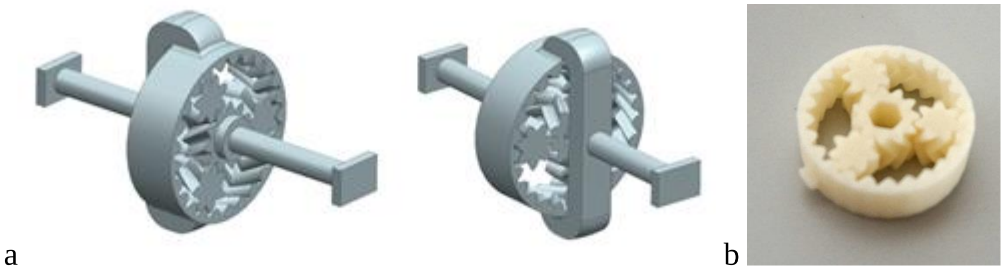


Figure 5: Planetary Gear I. a: CAD model front- and back-view. b: Printed part

Figure 6 shows an approach to reduce the axial play in the joint. A pin connects both inner gears to one leg, whereas the other leg is connected to the outer gears (see Figure 6b). While the rigidity did improve significantly, the asymmetry is more distinctive and the whole bearing is much heavier.

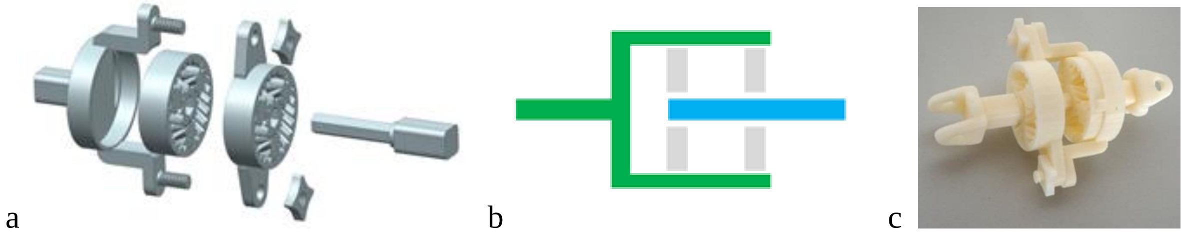


Figure 6: Planetary Gear III. a: CAD model. b: Schematic diagram. c: Printed part

In order to create a stiff and yet smoothly running hip joint, a casing for a metal ball bearing is fabricated (see Figure 7). The casing allows a firm yet removable connection to the metal bearing. This configuration results in a sufficiently rigid joint.

Table 1 summarizes the relevant properties of the different bearing configurations. The classification in Table 1 is made by a direct comparison of the different version of the hip joint regarding the labeled properties. Using the joints from Figure 4 and 5, one leg is connected to the outer gear and the other leg is connected to the inner gear. This causes a certain asymmetry, because the inertia of the inner and outer gear are different, which results in different dynamics for each leg. A symmetric behavior is beneficial, because it leads to a straight gait.

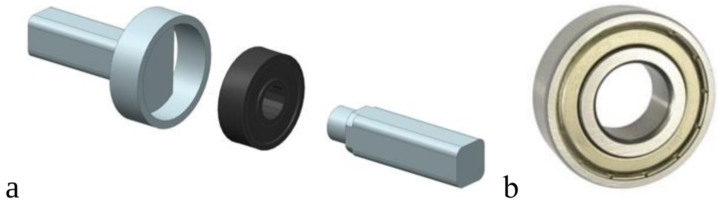


Figure 7: Casing for Metal Bearing. a: Setup. b: 608zz Ball Bearing

Hip Joint	Smooth & constant friction	Rigidity of center axis	Symmetry	Weight	AM only	Feasible for AM
Bearing I	0	0	-	-	+	-*
Bearing II	0	0	0	0	+	+
Bearing III	0	0	0	+	+	+
Planetary Gear I	-	0	0	+	+	-*
Planetary Gear II	-	-	+	0	+	-*
Planetary Gear III	0	+	-	-	+	+
Insert Element	+	+	+	0	-	+

Table 1: Overview Hip Joints,
Legend: + Good performance, 0 Average performance, - Poor performance
*could not dissolve support material

Legs and Feet

To connect the hip joint to the legs several connection methods are considered. Figure 8a shows a pin connection, where a holding device connected to the hip joint can be pinned to the leg. The connection is robust and allows for straight forward fixing and unfixing.

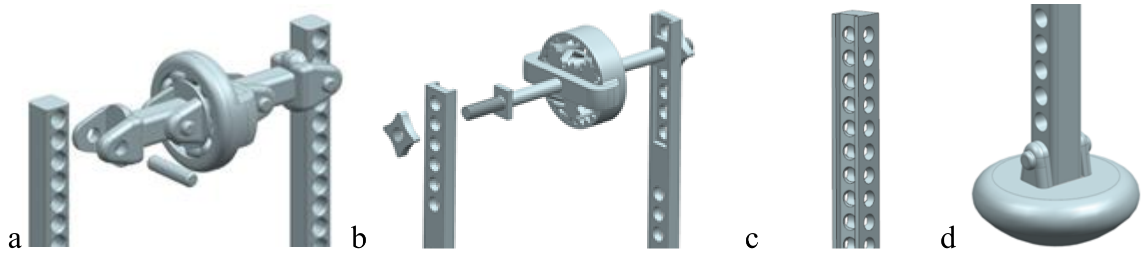


Figure 8: Legs, Feet and Connection. a: Pin Connection. b: Screw Connection, c: Leg, d: Connection Feet – Leg

To obtain a pin connection where the pin can be inserted in the hole with the right amount of friction, the orientation of the component in the printer plays an important role. If the orientation of the hole in the printer is as in Figure 9 on the left, the diameter of the holes has to be increased by 0.05 mm. Placing the hole as in Figure 9 on the right fabricates a smoother edge of the hole.

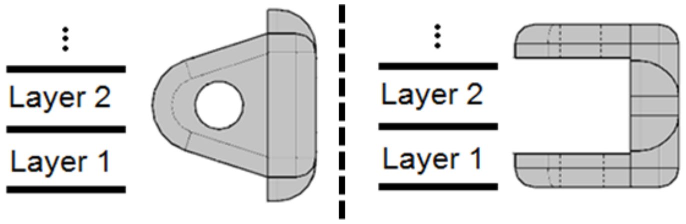


Figure 9: Orientation of Components in the Printer

To build a lighter connection, a screw connection is designed (see Figure 8b). Figure 8a and 8b show the two leg designs with their different connection types. The pin connection requires holes perpendicular to the center axis of the hip joint, whereas parallel holes are required for the screw connection. The leg in Figure 8c shows a configuration that allows use of both connection types. The pin connection can also be used to connect the feet to the legs (see Figure 8d).

Extension Elements and Weights

As described earlier, Colman and Ruina's Walker (Figure 1) requires an element allowing to shift the center of mass and influence the moment of inertia. Figure 10 shows a design for the extension element on which balancing weights can be attached.

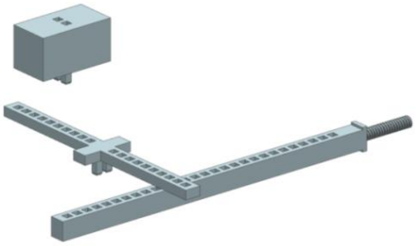


Figure 10: Extension Element

The weights and extension elements are connected by two pins that can be plugged into their counterpart. Different approaches have been tried varying the size of the holes and pins. Bigger holes simplify the fixing and unfixing of the weights and are less prone to breaking. On the other hand the shifting increment rises with bigger holes and therefore reduces the accuracy in the shift of the center of mass. The extension element can be fixed on the leg using the pin or screw connection presented in the previous section. Moreover, those connections allow shifting the center of mass along the z-axis (see Figure 3 for coordinate system).

Experiments and Results

The experiments are conducted on a ramp of varying slope shown in Figure 11. Two rubber stickers with high adherence to prevent slipping are attached on the top of the ramp. A stable gait for Ruina's passive walker was not found in simulation, but only found by experimenting with a physical model in [8]. Therefore it is crucial to be able to shift the balancing weights after printing to experimentally find a stable gait. Another reason for the need for adjustability is the inaccuracies introduced by the FDM process. The initial state of the passive walker is induced by hand. Several iterations show that it is beneficial to tilt the walker towards the stance leg, which is in contact with the ground, and to rotate the swing leg backward. This proves to be an initial state, after which several stable steps are likely to follow.

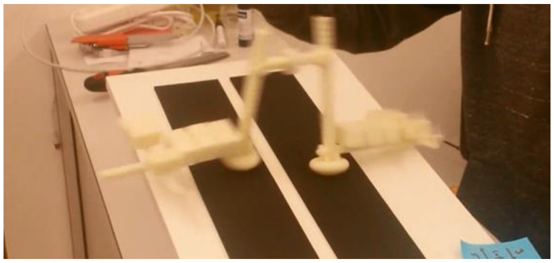


Figure 11: Experimental Setup

The first prototype shown in Figure 12a consists of a 3D printed bearing as shown in Figure 4 as a hip joint. Both the hip joint and the extension element are fixed on the leg with pin connections and are therefore adjustable.

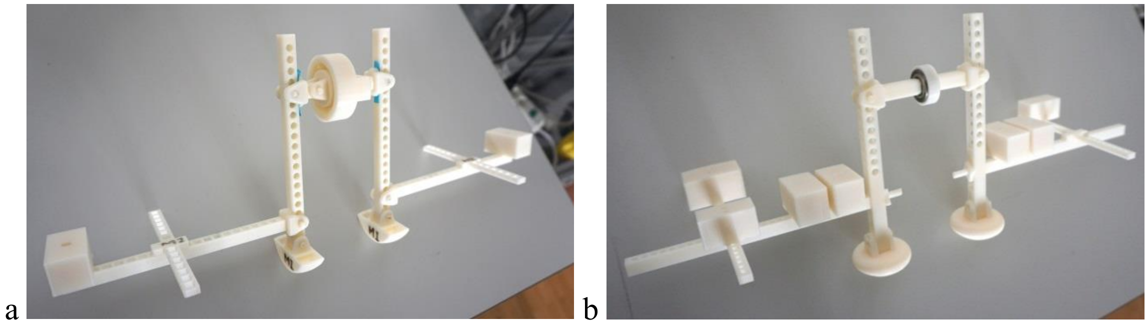
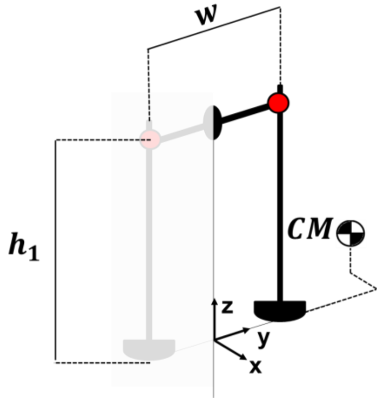


Figure 12 a: Prototype I, b: Prototype II

While conducting experiments with Prototype I, the following complications are observed. It tends to fall forward or backward, due to the high center of mass. The shifting increments of the balance weights are too large. The bearing is not stiff enough, meaning the center axis tilts easily. Using the planetary gear as a hip joint did not show a considerable improvement in the gait.

To lower the center of mass for Prototype II (see Figure 12b) heavier feet are used and the hip joint is replaced by a metal bearing. Using a metal bearing also reduces the play in the center axis. Designing an extension element with smaller holes reduces the shifting increments of the balancing weights.

Conducting experiments with Prototype II shows a stable gait for about nine steps. This means that the axial stiffness of the metal bearing as a hip joint is essential for a stable gait, which could not be achieved with the FDM produced bearings. In Figure 13, the mechanical properties of the left half of Prototype II are given. The walking direction is in positive x-direction.



$CM_x, CM_y, CM_z\ [mm]$	-3.4, 88.1, 48.8
$I_x, I_y, I_z\ [kg\ mm^2]$	1627, 437, 1260
$I_{yz}, I_{xz}, I_{xy}\ [kg\ mm^2]$	401, -17, -66
$R_{Foot}[mm]$	27
$h_1\ [mm]$	126
$w\ [mm]$	40.5
$m\ [kg]$	0.111

Figure 13: Parameters of Prototype II; All values for the left half of prototype

Figure 14: Kangaroo, a: Picture, b:Setup

The kangaroo, as shown in Figure 14, has four points that can be in contact with the ground, which makes it easier to achieve a stable gait as little balancing is needed. From a template [9] the form is adopted and the Planetary Gear I is used as the hip joint. Two pins connect both legs to the body of the kangaroo. The experiments using this passive walker shows that a stable gait is possible with this configuration, which is completely printed using FDM.

Discussion

Obtaining a stable gait with a FDM printed passive walker with a similar configuration to the Tinkertoy design is hard to achieve. The stable gait depends on many factors. The hip joint has to exhibit a certain rotational smoothness that has to remain constant over one step. With 3D-printed hip joints, this property is hard to obtain while keeping the axis rigid. A more rigid hip joint reduces the smoothness and vice versa. A suitable compromise could not be found in this project. In addition to the smoothness and rigidity, the hip joint has to exhibit symmetric behavior resulting in identical dynamics for both legs. Using a metal bearing eliminated the problems and showed an improvement in the walking behavior.

The kangaroo (see Figure 14) does not require much balancing in order to achieve a stable gait due to its configuration. Without this requirement, the FDM planetary gear allows a stable gait, even with the known imprecision. The kangaroo shows that stable passive dynamic locomotion is achievable using only FDM printed components.

Both configurations can be printed in one job. However, they are printed in parts and fully assembled after printing. When printed as an assembled prototype, there is support material added in the bearing. After removal of the support material the bearing surface is rough. The bearing of the kangaroo in Figure 14 is designed to be printed without support material. However, if the whole kangaroo is printed in one job with the legs already attached, the bearing would be filled with support material and would not operate as smoothly after support material removal. However, it is expected that it will be possible in future work to print a fully assembled working model by adjusting the layout of the assembly.

Conclusion

Two different configurations of existing passive dynamic locomotion robots, a Kangaroo and a Tinkertoy design, are redesigned to be fabricated using low cost FDM. A fully working prototype of the Kangaroo configuration with a more robust gait is printed in one job and tested successfully thus demonstrating a passive dynamic locomotion robot fabricated only out of FDM parts. For the second Tinkertoy configuration, which has a more sensitive gait, different types of FDM printed joints are designed and tested. However, a stable walk is obtained only by adding a metal bearing to the FDM parts. Moreover, a modular structure of the robot is used, allowing the exchange of parts as well as changing system parameters after printing, for example the center of gravity, which is crucial in the experimental testing and fine tuning of this type of passive walker. Different connection elements and feet are designed and tested. Through the success of the Kangaroo with an FDM printed planetary gear, a new approach to 3D printing of passive dynamic robotic systems is shown.

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