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Design of a Biomimetic Rodent Robot

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***Abstract*—In this article we describe the design of a modular, low cost, biomimetic robot created to mimic the size and locomotion of a common rat (*rattus norvegicus*). The created robot is untethered, easy to use and simple to produce; it thus can be used as a universal research platform. It is based on tendon-driven actuation, which allows for a compliant leg design and enables generation of open-loop controlled, simple locomotion patterns: trotting forward, backward as well as turning left and right. Small biomimetic robots can be useful for behavioral studies in combination with animals or for new, efficient types of locomotion, transportation and exploration systems. They are however challenging to build as mobile robots, since their size limits the use of common-sized actuators, as well as the use of large, long lasting power supplies.**

***Index Terms*—mouse, robot, walking, biomimetic, tendon-driven**

I. INTRODUCTION

Research on legged robots dates back to the 1960s with the first autonomous quadruped being the "Phony Pony" created by McGhee and Frank in 1966 [1]. Since then, quadruped robots have been improved constantly. Legged robots can cope, compared to wheeled ones, with a broader range of terrains, thus efficiently walking quadrupeds could work in mines as well as carry loads through disaster areas [2]. One example of such a quadruped would be "SpotMini" created by Boston Dynamics [3].

Replicating not only one part of a biological system but trying to mimic complete animals allows for applications closer to the research areas of biology. The robots thus created can be introduced into environments inhabited by their biological counterpart and interact with them, as in the research done by the Takanishi laboratory, where a rat robot was used to examine the social structures of rat society [4]. Another rat-like robot was built by Laschi, to see if it could teach a rat to push a lever to get food. The experimental subject was however not motivated to learn, as it could get the food from the robot pushing the lever [5].

Rodents, like the common Norwegian Rat (*rattus norvegicus*), have been used in physiological research dating back to 1828 and mice (*mus musculus*) to 1850. The mouse and the rat make up almost 80% of all research animals used in the European Union, further showing the importance of rodents in scientific research [6].

From a robotics point of view, rodents are of interest for their physical capabilities. Both, rats and mice, are capable of running on and climbing most types of electrical wire or rope as well as most rough vertical surfaces. However, currently there is no rodent robot to be found, which tries to bring all the advantages of the animal physiology into one structure. Some basic shapes with varying motion range could be replicated [4], [5] as well as certain capabilities like climbing [7], but none of these works tried to build an extensive replication of a rat with compliant actuation, but rather focused replications of specific abilities. This article describes a first step to create a new, more rodent-like and thus more generally applicable robot. It is in parts based on previous work done by Eva Siehmann [8].

II. ANATOMY OF RATS

In this report we will focus on rats, as those animals are larger, which simplifies a robotic adaption. Typical representatives of the branch *rattus norvegicus* have an average snout to rear length of 170-210 mm and a tail length of 200-230 mm. The weight ranges from 250 to 400 g and the speed can be up to 0.8 m/s [9], [10].

The skeletal structure of a rat can be seen in Figure 1. The primary focus of this work was the hindleg, which consists of the ilium, ischium and pubis, making up the pelvis, followed by the femur and in conjunction the tibia and fibula. Finally, the tarsals and metatarsals make up the foot. The whole skeleton of the rat shows a curvature in the spine, which changes, depending on the rat's motions [11].

As the rat is already well researched, there is data on the angles between the leg joints available in Fischer et al. [9], which was used as a basis for this work, as well as x-ray videos of rats, kindly provided by the archive of the Jena Collection of X-ray movies [12].

III. ROBOT DESIGN

The Prerequisites for this robot are to be similar to a common rat in size, weight and appearance, as well as to be able to adequately reproduce the quadruped walking motion. Additional requirements are to be low cost, modular and simple to build and control.

For the design, the anatomy as described above was used. For the actuation, inspiration was drawn from EPFL's CheetahCub [13]. This robot uses a combination of tendon driven and

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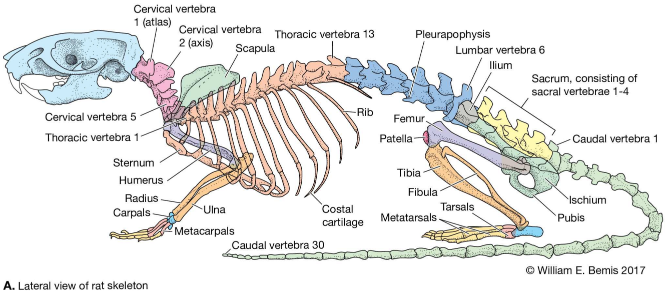


Fig. 1. Skeleton of a common brown rat. From Liem et al. Figure 8.18 [11], newest version provided by the second author William Bemis

direct actuation, acting on a pantograph leg. However, the CheetahCub is set up for a much larger animal and with that, a different step cycle than the ones of mice or rats. Hence, a new step cycle had to be designed, which can be seen in Figure 2. The first position (number one) is in the beginning of the stance phase with the foot on the ground, two is at the end of the stance phase with the leg at its furthest backward position, three is after liftoff and during the swing phase of the leg and four is at the end of the swing phase just before touching down again. The leg is under-actuated with two actuators controlling the rotation of the hip and the flexing of the knee while a spring is acting as extensor for the knee. The pantograph design of the leg, as adapted from the CheetahCub, allows also for a passive actuation of the ankle by using a two-way spring system. This has to be carefully defined to allow for enough contraction to generate force during stance as well as enough extension to allow the leg to be moved forward without "scratching" the floor during the swing phase. The toe is attached in a way that allows for a straight resting position but can be moved, as will be shown later.

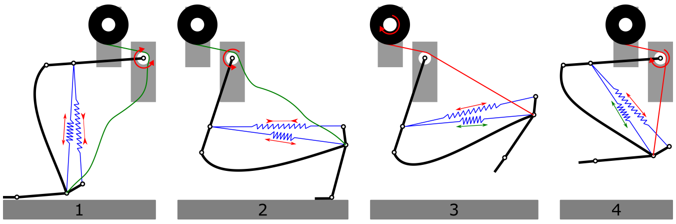
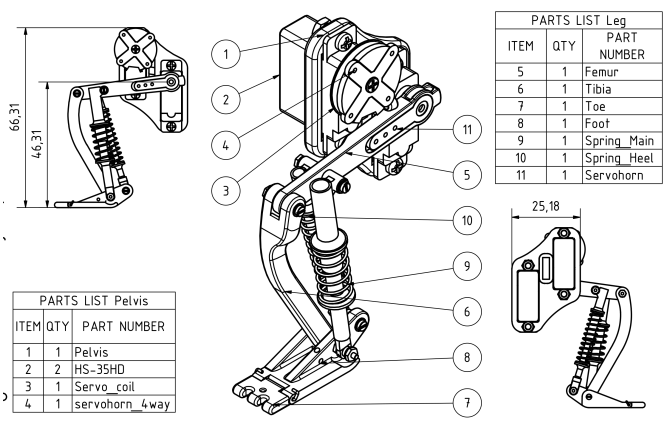


Fig. 2. This figure shows the proposed step cycle for the robot with the respective actuation.

To define the needed range of motion of the leg measurements of the rat's hindleg joint angles in the lift off and touch down position of the step cycle were taken from [9].
Using these bases, a first design of the hindleg was done using Autodesk®Inventor®Professional 2017. Here, the dynamic simulation tool was used to validate the previous calculations regarding the free lengths of the springs and now additionally the needed forces of the springs to support a robot of approximately 500g.
As the robot was to be as low cost as possible, the design was carried out with the use of 3D printing technologies in mind. The needed guides for the springs where created by hand using brass tubing cut to length and soldering them in place. The actuators used are RC Servos, which had the best force to size to cost ratio.



PARTS LIST Leg

ITEM	QTY	PART NUMBER
5	1	Femur
6	1	Tibia
7	1	Toe
8	1	Foot
9	1	Spring_Main
10	1	Spring_Heel
11	1	Servohorn

PARTS LIST Pelvis

ITEM	QTY	PART NUMBER
1	1	Pelvis
2	2	HS-35HD
3	1	Servo_coil
4	1	servohorn_4way

Fig. 3. This technical drawing shows the hindleg including some dimensions and numbered parts. Created with Autodesk®Inventor®Professional 2017

The final leg design can be seen in Figure 3. The pelvis needs to hold both servos firmly in place during walking. Additionally, a guide for the tendon was included between the coil and the femur to keep it aligned. A detachable tongue and groove joint was created at the connection to the spine for modularity and simple assembly.
The femur and the tibia are both fixed with clevis joints to the respective next bone, to keep the motion as straight as possible and to counteract the forces of the non centered springs.
For the feet, the design was reduced to two parts, the foot and the toe fixed to the foot via an axis made from copper wire. To introduce elasticity into the joint and add friction to the plane surface of the 3D printed feet, the latter were covered in silicone. As during a step, the heel starts to lift at approximately 2/3rds of the stance phase. The added toe is used to increase stability and propulsion force of the robot, as the toe stays fixed to the ground as can be seen in the second position of the step design in Figure 2.

Foreleg Design

Regarding the movement of the rat and using the already established hindleg, the foreleg could be reduced in complexity, compared to the former. The basic function is the same as for the hindleg, however the heel spring is attached to the end of the elbow acting solely as a tension spring, which leads to a much simpler assembly. The main spring is identical to the hindleg and the same design can be used, however an increase of the overall length had to be made. Also, the main force during stance is now generated by the heel spring, pushing the toes against the ground. The pelvis could be mirrored and reused for the scapula, a more intricate design will be done in the future. The whole assembly can be seen in Figure 4 at the bottom.

Design of the Body

The central skeletal structure of the robot's body serves as a base for mounting all the legs as well as the head and tail as well as holding the electronics and the battery. In addition to biological resemblance, the rib structure encases the required electronics and keeps the wiring away from moving parts. The design was inspired by the rat's skeleton, where the ribcage is attached at the thoracic spine and does not cover the whole body. This allows for more mobility in the lower spine region, which will be especially important for later designs with an active spine. The hindmost rib loop is needed to keep the cables in place and away from the moving hindlegs.

To easily place and replace the electronics, a lid was placed at the thorax to be screwed in place. The head and tail as well as all the leg-modules are also held in place by screws and easily detachable, to add and/or swap different designs when needed.

Control

As the whole robot was designed to be untethered, the complete electronics had to fit within the body and still be capable to drive the at least 8 servo motors for basic walking and leave capabilities for additional sensors. To achieve these specifications, the now discontinued Intel®Edison Compute Module [14] was chosen, based on its computational power and small size. As addition, extension blocks from SparkFun [15] were used for servo connectivity, AD conversion, GPIO connection, as well as an IMU and basic USB access.

The control software was written in C++ with a simple interface to be able to remotely set up and control the robot. An open loop gait controller was implemented, producing five fixed motion patterns. Those are a lateral sequence walk, a simple slow trot as well as a backwards trot and patterns for turning left and right; together they, allow for a directional control of the robot locomotion.

In the trot two legs are always paired and are actuated in the same way, such that always two legs are on the ground and two in the air. With the lateral sequence walk, each leg has an individual stance and swing phase with two or three legs on the ground simultaneously. For curve walking, the trotting gait was adapted, such that the legs on the inside of the curve have a shorter stance phase than the ones on the outside, while keeping the same walking pattern.

IV. RESULTS

The resulting robot of this work as can be seen in Figure 4. The whole robot can be separated into the leg-modules, head, tail, body and electronics. The head has, apart from aesthetic purposes, a balancing function. It is filled with weights, to allow for a more stable stance and walk. The tail is for purely aesthetic purposes, to underline the biomimetic design. It will be used to add to the walking stability, when an actuated spine and tail are included in the future.

The robot parameters are shown in Table I in comparison with the respective values for a common *rattus norvegicus*. As can be seen, it was possible to keep the robot within the typical values for weight and length, not counting the tail. The main difference can be seen regarding the speeds of the robot and the rat. With 0.06 m/s the robot is by a factor of about 10 slower than the animal. The limiting factors here are the motor speed, as well as the size of the coil and the attachment point of the string, both effected by the strength of the motors. In further testing, it could be determined, that the robot could lift up to 75 g in addition to its own weight and still walk forward.

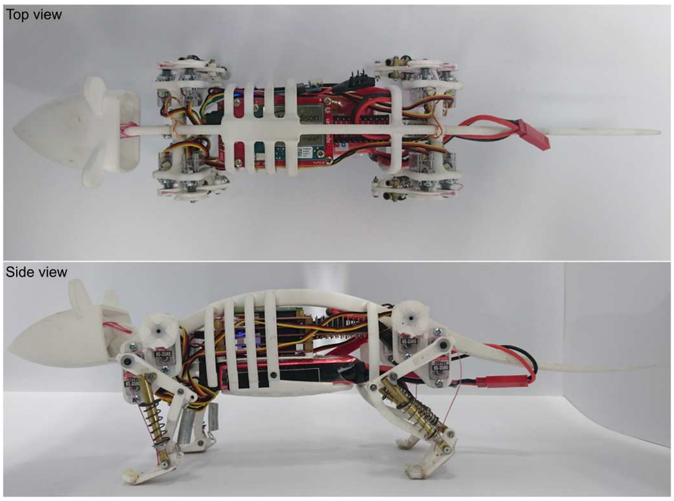


Fig. 4. These images show the final robot from a side and a top view.

TABLE I
DIMENSIONS AND WEIGHTS OF THE ROBOT AND *rattus norvegicus*. UNKNOWN VALUES ARE LABELLED BY '-' [9], [10].

Type	robot	*rattus norvegicus*
Weight (grams)	225	250-400
Length snout-rear (mm)	198,3	170-210
Length Tail (mm)	117,3	200-230
Overall Length (mm)	316	370-440
Overall width (mm)	72	-
Speed (m/s)	0.06	up to 0.8
Turn radius (cm)	20-40	-
Turn speed (m/s)	0.027	-

Walking Analysis

The robot can produce a stable walking motion, trotting forward, backward as well as turning left and right. The lateral sequence walk was found to be computationally infeasible with the used control architecture. The different leg designs for fore- and hindleg create a difference in step length, which in the animal is compensated through the motion of the scapula. Here, the step length for the hindlegs was reduced, as long as no actuated scapula is implemented, leading to a reduced overall speed.

It was found, that the precision of the leg assembly, especially the bearings and the springs, as well as traction, influenced the controllability of the walking direction. The bearings were drilled slightly different for the left and the right forelegs as well as the spring forces imbalanced. Together with differences in friction between the feet, this lead to a non straight forward walk as can be seen in Figure 5. Here, the forward movement has a clear inclination towards the left, whereas the backward movement is achieved in a straight line. The left curve during forward walking can also be partly explained through a curvature of the spine, caused by the battery wiring pushing against the last rib. As this is in the lumbar region of the spine, the backward walking isn't influenced as much.

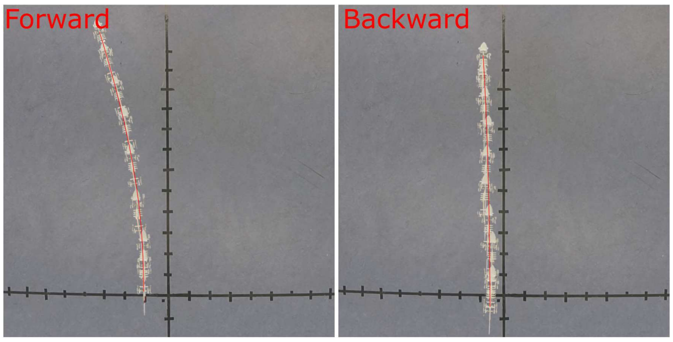


Fig. 5. Forward and backward walking of the robot over a length of 1,2 m. One grid mark is 10 cm. Created by overlaying multiple frames of a video.

The robot was also programmed to walk in curves, which showed different results depending on the turning direction as can be seen in Figure 6. The walking radius is currently not deterministic, since many factors seem to influence it, namely the friction of the feet as the walking algorithm relies on rotating on the left foot for turning left and vice versa.

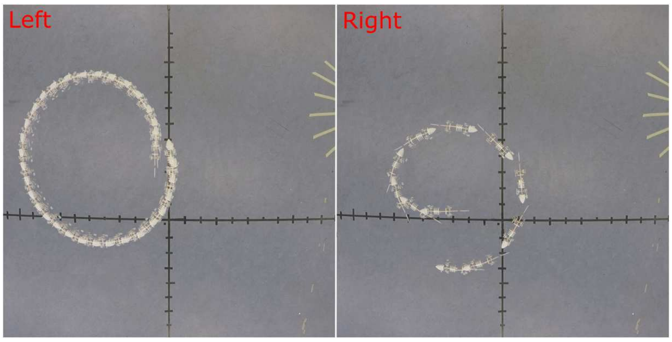


Fig. 6. Walking radius of the robot as seen from above for turning left and right. One grid mark is 10 cm. Created by overlaying multiple frames of a video.

Concluding the walking evaluation, the robot can safely walk, without the risk of falling over. While remotely controlling the robot, it can be steered through a room over different surfaces and even small obstacles. The later is limited by the lifting position of the hands and feet.

Evaluation and Outlook

The robot does not need any setup. Upon connecting to the robot's WIFI network the controller can be started via an ssh connection, which makes it an easy to use system. The hardware cost is below 500 € which can be regarded as low cost in the field of walking robotics. This could mainly be achieved by using 3D printing and off the shelf electronics. The most costs are caused by the motors, with about 20 € a piece. They were found to have the optimal balance between cost, size and torque, however, are also the limiting factor for the speed and weight of the robot. Any improvement on the motors will have to include custom build hardware or electronics, in order to keep the current size and modularity. The Assembly of the springs as described in section III is not precise enough to guarantee a uniform elasticity for the different legs. Hence, further developments will include a more precise design for holding the springs in place. Additionally, the design of the 3D printed parts will be improved, to allow for a more stable assembly, especially regarding the joint connections, which have to withstand transverse loads created by the springs. For a better control of the turning capabilities, an actuated spine will be implemented in the future. This should improve the current course keeping ability of the robot as shown in section IV. During walking the robot is also tiling towards the lifting hindleg. Here improvements may be possible by either compensating via an additional degree of freedom in the hip, or with an actuated tail. Those improvements aim not only to improve the robot, but also to get closer to the model animal regarding its capabilities and together with a more sophisticated control its physical behavior.

Comparison to current robots

Finally, the robot can be classified in comparison with other robots and the common rat. As shown in Table II, the currently known robots, resembling rats, or rat sized robots with mammalian type walking, are compared to our robot in dimension, weight and speed. The newly created robotics system is the smallest in height and comparable in width. Without the tail, the robot is also the second smallest with a length of 208.6 mm. Regarding the weight, the robot is the lightest and closest to the biological model, together with the robot by Patanè et al. [5]. In speed, the robot is behind the currently fastest CheetahCub which is representing seven comparable robots created at the Biorobotics Laboratory of the EPFL [16]. As the Cheetah Cub is the fastest and smallest representative, the others are not listed here.

These results make the current robot one of the best biomimetic robots for rats in size and weight, having the advantage of being very close in appearance, as well as being modular and cheap. One significant drawback currently is the missing actuation in the spine, which will be added in future versions.

V. CONCLUSION

Within this work, a biomimetic hind and foreleg were created and used to build a mobile biomimetic rodent robot. The created pantograph leg design allows for a slim leg design and together with the used springs introduces elasticity

TABLE II

Comparing the robot of this work to robots of different design and *rattus norvegicus* [5], [9], [10], [16]–[18]. Unknown values are indicated by '-', dimensions are in mm in the order length x width x height, weight in kg and speed in m/s.

Robot	Dimension (mm)	Weight (kg)	Speed (m/s)
This Robot	316 x 72 x 85	0.23	0.06
LittleDog [18]	340 x 143 x 180	3.00	-
Cheetah-Cub [16]	210 x 100 x 158	1.10	1.42
Cheetah-CubS [16]	205 x 100 x 105	1.16	0.36
WR-1 [17]	270 x 130 x 110	1.15	0.02
WR-2 [17]	240 x 70 x 90	0.85	0.03
Rat-like robot [5]	146 x 69 x -	0.34	-
rattus norvegicus	length 370 - 440	0.25 - 0.4	0.1 - 0.8

into the system, which enables the legs to adapt to impacts and different surfaces as well as mimic the morphological computation of rats during walking.

It could be shown, that, using this design, an untethered robot within the average dimensions and weight of a common rat *rattus norvegicus* can be created, which is capable of a forward trotting gait as well as turning and walking backwards.

The additional perquisites of low cost, modularity and controllability as stated in section III could be met, enabling the use of this robot as a general research platform.

Comparing the robot to other current similar robots and to the biological model, as in Table II, shows, that the created robot lacks speed but is comparable in dimension and weight and is currently the closest to resemble a rat.

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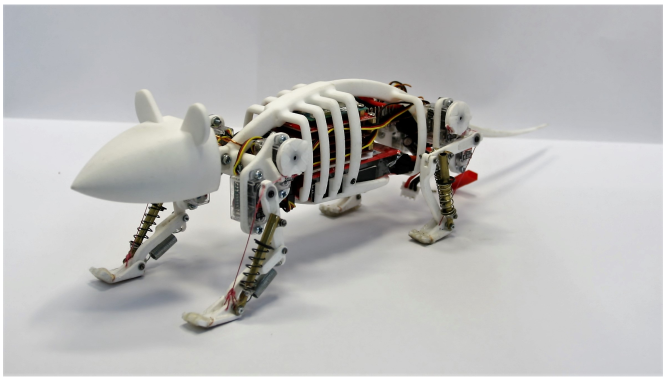
VI. APPENDIX

Datasheet of the NRP Mouse, to be used as stand alone Description.

NRP Mouse V1 (Walter)

- **Quadruped Biomimetic Robot**
- **Easy to control via WI-FI and Bluetooth**
- **Tendon driven**
- **Modular**
- **Trotting Speed: 0.06m/s**



Introduction

The NRP Mouse is a Biomimetic robot, which tries to mimic the appearance and motion of a Rodent. It is designed to be modular, to allow an easy exchange of leg designs. The Use of off the shelf parts and 3D printing technology, allows for cheap production.

Physical Characteristics

Length	316 mm
Length Scapula-pelvis	125 mm
Height	85 mm
Width	72 mm
Weight	225 g
Max. Payload	≈ 75 g
Material	PA 2200, Eos / Brass

Motion

Motors	HS-35HD Ultra Nano Servo
Degrees of Freedom	8
Speed	0.06 m/s
Turn radius	20-40 cm
Turn speed	0.027 m/s

Specific values during trot	Hindlegs	Forelegs
Max. Step length (mm)	64-83 mm	59-63 mm
Hip angle range (deg)	56.8 deg	51 deg
Knee angle range (deg)	21.5 deg	33 deg
Ankle angle range (deg)	29 deg	65 deg

Control

The robot can be controlled via a simple terminal interface using Wi-Fi or direct USB connection. Another possibility is the use of a AR App. Own controllers can be created using a C++ class to interface with the robot.

Power

Battery	7,4 V 1000 mAh LiPo
USB Power	5 V
On Board Power	5 V; 3,3 V
Run Time	≈ 1 Hour continuous walking

Inputs / Outputs

GPIO	16 (4 UART)
PWM	12 (8 occupied)
ADC	4 12 bit Channels
USB	2 (1 OTG)
IMU	9 degrees (3-axis accelerometer, 3-axis gyro, 3-axis magnetometer)

Processor: Intel® Edison

SoC	dual-threaded Intel® Atom™ CPU at 500 MHz and 32-bit Intel® Quark™ microcontroller at 100 MHz
RAM	1 GB LPDDR3 POP memory
Flash	4 GB eMMC (v4.51 spec)
WiFi	Broadcom* 43340 802.11 a/b/g/n; Dual-band (2.4 and 5 GHz)
Bluetooth	Bluetooth 4.0
Interface	up to 20 GPIO incl. UART, I2C, SPI and I2S
Power	3.3 to 4.5V
CPU OS	Yocto Linux* v1.6

Material Cost

Electronics	352.00 €
3D Prints	67.03 €
Mechanical Parts	60.47 €
Complete Robot	479.57 €

Project

This Robot was created by Peer Lucas at the Chair of Robotics, Artificial Intelligence and Real-time Systems as part of the Neurorobotics Plattform of the Human Brain project.

Contact: peer.lucas@tum.de
Web: www.neurorobotics.net

The research leading to these results has received funding from the European Union Horizon 2020 Programme under grant agreement No.720270 (Human Brain Project SGA1) and No. 785907 (Human Brain Project SGA2)