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A low-cost robot for multi-robot experiments

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***Abstract* — This paper presents a design for a low-cost research robot based on the chassis of a Hexbug Spider, a remote controlled toy robot. Our modification replaces the robot head with a 3d printed adapter part which provides space for sensors, a larger battery, and a microcontroller board. In a second part of the paper we address the manufacturing process of such a robot. The presented robot costs far less than 100 Euro and is suitable for swarm robotic experiments. The hexapod locomotion makes the robot attractive for applications where a two wheel differential drive cannot be used. Our modification is published as open hardware and open source to allow further customizations.**

Keywords— robotics; self-organization; swarm robotics; hardware; manufacturing

I. INTRODUCTION

Robotic swarms are gaining more and more interest in research. They take inspiration from nature in order to emerge collective behavior from interactions between robots and interactions of robots with the environment. A large number of simple robots can solve common complex tasks. Currently, software simulation is the most used method for testing of swarm behavior due to the hardware complexities and cost of robots. Such simulation is extremely complex and often inaccurate due to the poor modeling of the environment, which calls for a validation with real robots. Robots have been a focus of research and education for several decades. For example, the Lego Mindstorms series are very well known for providing kits containing software and hardware to create customizable, programmable robots. There are many document application cases of using Mindstorms in teaching or research, but the investment costs of approximately 350 Euro are often a problem for education purposes.

In research, investment costs of a couple of hundred Euro are a minor problem, since the main focus here is on programmable robots with sufficient sensors which can be used as a simulation model [1] and for later lab experiments [2]. However, with the upcoming field of cooperative and swarm robotics there is a need for acquiring a large number of robots. In case of swarm robotics this can mean even a few hundred robots. Multiplied by this number, investment costs are again very relevant. Furthermore, swarm robot experiments [3,4] and self-organization [5,6] require interacting robots (thus having sensors and actuators) that are compact in order to perform experiments at the scale of a lab room with hardly more than 50 square meters space.

In order to push development for ultra-low cost educational robots, the African Robotics Network (AFRON) called for a design challenge for a "10 Dollar Robot" which instigated the design and publication of new compact robot designs. Being primarily aimed at educational use, most of the designs come with some downsides (missing sensors, robustness) when being evaluated as a robot for swarm robot applications. On the other side, educational robots are not necessarily fulfilling the requirements for swarm robotics which we identify by the following requirements (properties) for (of) a robot:

- Affordable. The total price of one robot including additional modules should not exceed 100 euro. The body of the robot can be easily reproduced using a 3D printer.
- Swarm-oriented. The robots will be used in experiments with swarms and the components of the robot should enhance cooperation between robots.
- Customizable. The model can be changed in order to meet the requirements, for example, to add additional sensors.
- Open-platform. All models and blueprints of the robot are a freely available information and everyone can use, reproduce or modify them.
- Easy to use. Provide simple programming and user-friendly robotic implementation.

It is the purpose of this paper to present a robot designed in the spirit of these requirements with robust locomotion equipped with sensors suitable for swarm robot experiments. The robot builds upon a Hexbug Spider, a remote controlled toy robot, which provides elegant mechanics and sufficient sturdiness at low cost. The robot has been upgraded with local intelligence and sensors by replacing the part for the remote control receiver with a 3D-printed adapter for sensors, microcontroller and a larger battery.

II. RELATED WORK

The s-bot [7] is a differential wheel robot developed by the Laboratory of Intelligent Systems at EPFL. It was developed within the Swarm-bots project, and targeted to swarm robotics. The basis layout is circular with a diameter of 12 cm and a height of 15 cm. Besides locomotion, the robot features actuators for 8 RGB LEDs, a motor for turret rotation, moving and actuating of a front gripper and a side arm gripper. The weight is 660g. In overall, the robot is considerably complex at the cost of price and battery runtime.

The Khepera robot is a small (5.5 cm) differential wheeled mobile robot, introduced by Mondada et al. as a miniaturized robot aiming at control algorithm experiments [8]. Khepera became very popular among research labs and was used in evolutionary robotics. The Khepera robots are very compact and capable, but are comparably expensive. The current version Khepera IV sells for around 3000 Euro.

The e-puck [9] is a small (7 cm) differential wheeled mobile robot. The e-puck is open hardware and its onboard software is open source, which lead to a market with several companies selling the robot and, consecutively, a lower price than the Khepera. An e-puck still costs between 500 and 1000 Euro which makes a high investment for many of them in swarm robotic applications. Although the robot was originally aimed at educational purposes, the e-puck was quickly adopted by the scientific research community.

Lynxmotion is an established manufacturer of robot kits, including robot arms, biped walking robots, quadrupeds, hexapods, tracked and wheeled vehicles. Some kits provide features for designing an autonomous robot controlled by a BotBoarduino microcontroller board. The Lynxmotion Hexapod II robot, a six-legged walking robot instrumenting twelve servos (two per leg), has been used in early swarm robot applications, where a number of Hexapod II robots were controlled by a Robart III security robot [10].

The first generation of Lego Mindstorms was the Robotics Invention System containing two motors, two touch sensors, and one light sensor that could be instrumented by a controller brick. It was released in 1998, a Robotics Invention System 2.0 was available in 2000. In 2006, Lego issued the first version of the LEGO Mindstorms NXT kit which replaced the old system. Since then, a number of different sensors and actuators became available, including guides how to implement own sensors [11]. The NXT 2.0 kit was released in 2009, the current version EV3 was released in 2013. Teuscher et al. used Lego Mindstorms to build a minimal robot dubbed Romero aimed for experiments with individual and robot populations [2].

The Hexbug Spider and the Hexbug Spider XL are small and light toy robots controlled by an infrared remote control. The low cost of 20 to 30 Euro make it an attractive mechanical basis for extensions with local sensors and control. The Autonomous Spider group at buildsmartrobots.com suggested a modification of the Hexbug Spider by extending it with the EMGRobotics Low-Cost Robot Controller. This features an IR distance range sensor, a motor controller, and a TI MSP430G2231 16bit microcontroller and an AAA battery pack. The modified robot is able to turn left or right and walk forward or backwards autonomously.

AIBO (Artificial Intelligence Robot) is a four legged robot modeled to resemble a puppy introduced as an entertainment robot by Sony in 1999. AIBO came pre-programmed with a software mimicking desires and emotions such as love, search, movement, recharge, and sleep. The good locomotion abilities and the possibility to program AIBO made it an interesting platform for (cooperative) robotics, especially in robot soccer. However, Sony stopped production and distribution of AIBO by 2006.

The Kilobot [12] is a low-cost (part cost about 14 $) robot intended at collective robotics behavior applications. Kilobot uses two sealed coin shaped vibration motors for locomotion and communicates with neighboring robots via an infrared LED transmitter and infrared photodiode receiver. The slip-stick based locomotion [13] of the robot allowed for a small design and low cost, but comes with the drawback of requiring a proper surface and providing no odometry.

The origami inspired Segway robot from MIT is a low-cost robot build from 2D materials which is folded in a similar way to the Japanese art of Origami. The body is then equipped with actuation mechanisms and some electronics. The overall robot is a differential wheel robot controlled by a tinyAVR microcontroller [14].

III. ROBOT DESIGN

Our proposed robot design consists of the locomotion system of a Hexbug Spider where we attach a 3D-printed adapter for sensors, battery and microcontroller. The physical parameters derive mainly from the Hexbug Spider which has six legs that are spread within a diameter of 10 cm. The central body has a diameter of 4 cm which becomes wider above the legs and a height of 8 cm. The body has a clearance of less than 1 cm. The overall construction is able to step over edges of 5mm height or less. The mechanics provide a coordinated movement of all six legs to move the robot with a speed of 6 cm/sec. One moving cycle of all six legs takes 500 milliseconds. To change movement direction, the robot has to turn its head. A full turn takes 3 seconds.

A. *Mechanical Design*

The Hexbug Spider has as mechanical movement system with six legs and two small electric engines for simultaneous, coordinated movement of the spider legs. The two electric engines are each coupled with a gear box with proper gear train. One engine is used for rotary motion, the second for forward or backward movement according to rotation direction of the spider system. The leg coordination is quite sophisticated and is transforming rotational movement into directional movement of the six legs, in a kind that leads to up and down movement of the legs combined with forward and backward movement. This movement in a "plane" leads, according to the neighboring environment, to a directed and reacting movement.

The goal of the mechanical design of the robot is to yield mechanical robustness and reliability of movement in a below defined specific environment, as well as low energy consumption and low cost of overall design, aiming at light weight mechanical variants. Compared to the preexisting 'mechanical feet design' of the HexBug Spider system, also mechanical alternatives and adaptations shall be investigated, e.g. by improving the feet's friction on the surface.

Concerning the mechanical stability, this is functional for the existing system with regard to reliable and continuous movement. The net movement pattern can be regarded as complicated. The mechanical linking, is restricted to some joint-connections here shortly called "legs".

From the aspect of mechanical stability and steadiness in this application four aspects are central to reach the goals of the mechanical design:

- light weight of materials,
- high rigidity and suitably elasticity of materials,
- low friction of joint-connection and
- high transmission efficiency of the traction chain.

With respect to propulsion, or motion control two states can be distinguished: The normal or active mode and the passive or abnormal mode. In the first case, full control of the system is applicable with respect to a "normal" environment. In the passive mode control is lost, and the environment is not properly suitable for the mechanical system, as it has "new" properties, that the "mechanical system" is not prepared for.

Hence for the judgement of the situation concerning the two modes it is of ultimate importance to have suitable information about the environment of the system in real time.

The actual materials consist of thermoplasts, which are typically injection molded, as it is part of a toy that is mass produced. In this project the old system – the original toy with its mechanic - is, used, modified or 3D printed. For 3D-printing also thermoplasts are used, namely PLA or ABS are most widespread. Mechanical stability can differ here in relation to the "density" which is printed und can be equal to injection molded material or increasingly less with different infill grades for 3D printing. In fact with lower infill grades also a lower weight of the parts can be achieved. As a result, only the forces needed for the material should be implemented, and these are decreasing when the weight goes down, as the systems mechanical stability is depending on self-propulsion, which is related to active mode, where the forces on the parts of the mechanical system depend mainly on its own weight and partly on those of the implemented propulsion system.

A second influence factor is given in case of an abnormal function, that is e.g. when the system is falling down "high" heights, due to loss of propulsion control. This mode may be called passive modus, versus active modus under "normal" conditions. Light weight systems have here the advantage that increased elasticity (E-module) coupled with rigidity provides survival properties. These increase the "probability" of preservation of mechanical und functional system structures. For this purpose especially fibre enforced materials are of advantage, which can also be 3D-printed for example with the Mark One 3D Printer [15, 16]. The advantage of this method is that only those locations of the construction components of the mechanical system need to be reinforced, that are affected by higher forces. The main focus is hence the identification of the locations which have to be positioned strategically and then to be fibre reinforced accordingly. By means of this method the constraints, stability, elasticity, rigidity and (light) weight can be "optimized" for the system. The result is a system with maximum "survival" probability under the aspect of self-propulsion and self-inflicted accidents or uncontrollable situations due to environmental conditions.

The low friction of the joint connection has a direct influence on the transmission efficiency and hence the "power" needed for the electrical engine, which affects weight of components which are needed to supplement the energy source. By means of the supporting system this is the transmission efficiency of the electric engine, of the gearbox of the joint connections of the "legs" mechanic and of the transmission efficiency of the leg movement to a directed movement of the system in the actual environment.

Concerning the active and the passive mode two principal causes are relevant for this spider-legged "locomotor system". Firstly the environmental conditions in general, i.e. principal surface conditions like the phases, solid, liquid gaseous, the surface topology like roughness, type of plane or dynamics of the surface. Surely not all those environments can be controlled, or even predicted if they are suitable for the system. Hence a restriction must take place to make possible also, as a consequence, restricted conclusions. For this the system investigated shall be plane and contain rigid environments with allowance to surface roughness and form to a defined extent. Also the end of a plane can be given, by means of some kind or type of wall or as an open system, e.g. a gap leading to uncontrollable passive mode. Here the topology and its interaction with the robotic system, determines the switching between active and passive mode.

Secondly the interaction between legs and environment, starting always with active "normal" mode is depending of the friction, i.e. the transmission efficiency of the legs with the environment. The scaling properties have here great influence on the system transport efficiency which can be defined with respect to time and energy needed per covered distance in a certain environment. For the scaling the factor M_μ can be defined as

$$M_\mu = \frac{\mu_1}{\mu_2} \cdot \left(\frac{L_1}{L_2}\right)^{D_f} \cdot \frac{\rho_1 \cdot g}{\rho_2 \cdot g} = \frac{F_{R1}}{F_{R2}}$$

Here, 1 and 2 indicate the model of size 1 and size 2 with respect to scaling. μ_1 and μ_2 are the friction coefficients, L_1 and L_2 are the Cartesian lengths of the system – the robot system in this case. D_f is the fractal dimension, which is 3 for a gap free 3-

dimensional object like, for example, a cube and two for a gap free plane, e.g., a square (see also [17]). F_{R1} and F_{R2} refer to the friction force limits tangential to the plane, which is the limit between full transmission efficiency (100%) of moving legs and gliding respective partial transmission efficiency (<100%) or also, in the context here, uncontrollability and or passive mode.

When the densities are the same with $\rho_1 = \rho_2$ and also the friction coefficients are the same with $\mu_1 = \mu_2$ the so gained scaling law gives

$$M_\mu = \left(\frac{L_1}{L_2}\right)^{D_f} = \frac{F_{R1}}{F_{R2}}$$

where D_f is between 2 and 3 for porous bodies, like the spider construction. Here the ratio M_μ gives the scaling law for the different forces on the ground, as it can be seen that, when scaling down geometry, the friction forces goes down with the power of $1/2$ to $1/3$ for the same material pairing meaning the legs respective the surface on the contacting area. As a consequence the loss of controllability is affected directly by this scaling law, with respect to scaling model size (see also [18]).
A second influence on the friction factor and hence transport transmission efficiency, is due to the geometry of the spider and its dynamic leg movement, and hence the movement of the center of gravity, which affects dynamically active or passive mode, according to dynamically changing friction forces F_{R1} respective F_{R2} (compare also [18,19]).
The situation to retain control out of uncontrollability – passive mode in "normal environment" - after an uncontrollable situation – passive mode in "abnormal environment"- in a then controllable "normal" environment – active mode in "normal environment" - is not investigated in the project. Normal environment is in this context the previously defined environment, abnormal environment everything else. This can be investigated in a following project, and is part of increasing survivability probability of the system or also resilience. In this context collaboration with cooperation species of the "environment" could be of advantage. For this purpose the triangle environment, cooperating mobile environment, and mechanical supportability are to be investigated.

B. The influence of the result of the mechanical design goal on the research is to have a more or less optimized robot system with regard to: The energy consuming system, the stable and reliable mechanics, the elements with open hardware and the costs to implement the mechanics.Adaptation

For the current prototype, our modification starts with partly disassembling the original robot – the head of the spider needs to be removed in order to get access to the motors. As replacement of the head, a 3D-printed adapter part is attached to the robot (see Figure 1). The adapter has the structure of a funnel that widens on the top. At the end a crenellation allows for attaching a number of sensors. Inside the funnel, there is a space for a 9V block battery and an Arduino Mini Pro board. We used a DRV8835 dual motor carrier to connect to the two motors of the robot chassis. Speed of the robot can be controlled by PWM (Pulse Width Modulation) outputs of the Arduino board connected directly to the DRV8835 board. The robot has six TCRT5000 reflective optical sensors which allow to sense distance up to 5 cm. They are connected to an ATtiny84 microcontroller which processes data from the sensors and communicates with the Arduino board. Figure 2 shows the assembled final robot.

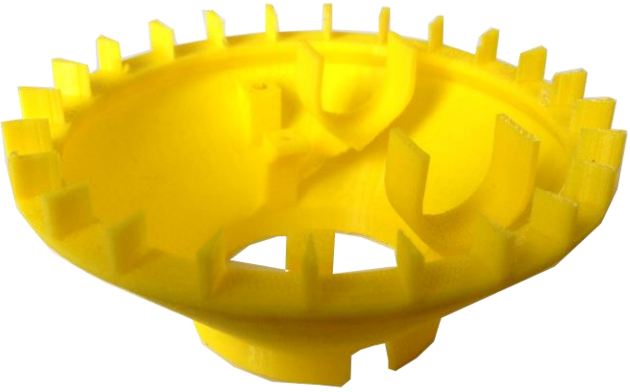

Fig. 1. Adapter part

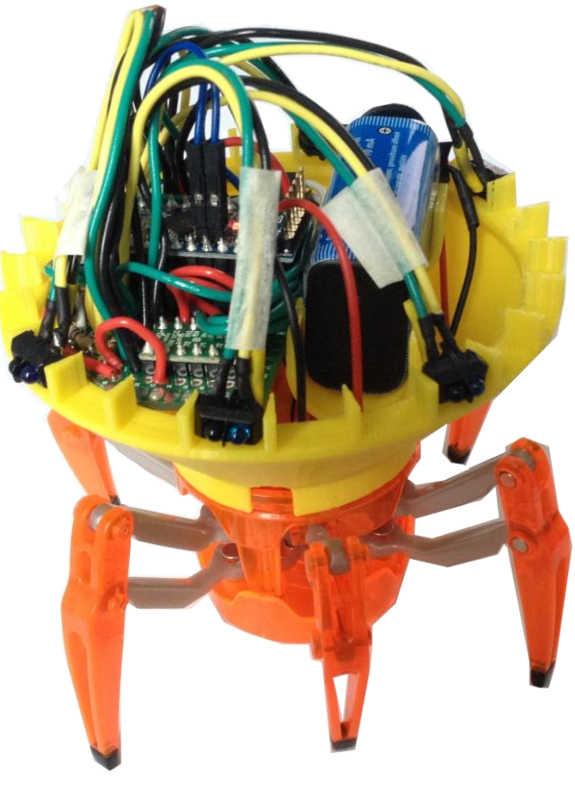

Fig. 2. Prototype of overall robot

There is a software library written in C/C++ programing languages to control the motor speed and read information from the proximity sensors. This library can be easily imported into

Arduino IDE to implement a firmware for the robots. A developed firmware can be uploaded to the robot using an FTDI breakout connected to the Arduino board. To program swarm behavior, we will use a tool like FREVO [20] which creates an Artificial Neural Network (ANN) using an evolutionary algorithm and a simulation. The evolved ANN can then be exported to be run on the Arduino. Typical ANN networks created this way have a manageable number of 10-20 neurons [1], which can be easily simulated with regard to processing speed and memory by the employed microcontroller.

IV. INNOVATIVE TEACHING APPROACH FOR ROBOT PRODUCTION

We will combine the production of the low-cost robot with the development of an innovative hybrid approach for teaching operations management based on the concept provided by Reiner et al. [21]. In particular it integrates queueing theory and business games. The related innovative learning concept is motivated by Deming's Plan-Do-Check-Act (PDCA) cycle, well known as the basis for continuous improvement "Kaizen" [22]. The prerequisite is transition from robot design (including prototyping) to production. The transition process will provide all the relevant information and documents for production, i.e., bill of material, equipment master data, work instructions, inspection instructions, and assembling instructions. State-of-the-art approaches will be applied to support this process, in particular quality function deployment seems to be appropriate [23].

There are three objectives that can be addressed with this production environment. First, students will analyze different manufacturing strategies, in particular push versus pull and lean production based on Kanban, CONWIP, etc. The applied quantitative modelling approach based on tools using queueing theory (e.g., MPX and RapidModeler) will help to understand the mechanics behand the principles of Factory Physics [24]. Classical issues are the impact of variability of demand as well as service times and resource utilization on system performance, i.e., flow time and WIP [25].

Secondly, the analyzed manufacturing strategies will be implemented under consideration of different demand scenarios. Here, two main results will be generated, the "ordered" quantity of robots as well as "real" data of the production process that can be used to check and evaluate the analysis carried out before. This will be a "special" and unique learning experience for the students.

Thirdly, by application of the last step of the PDCA cycle (i.e., standardization and reflection) the optimal production method can be transformed to an "industrial" production process. Optimality will be derived based on the overall costs (derived from cost drivers like labor & equipment utilization and average on hold inventory) and satisfaction of customer requirements (measured by the fulfilment of service level agreements).

The side effect of this "manufacturing game" are the necessary robots for the multi-robot experiments. The application will provide empirical data that can be used to improve the manufacturing efficiency as well as effectiveness and to improve the teaching & learning experience.

V. OUTLOOK AND CONCLUSION

We have presented a robot design as an extension to the Hexbug Spider toy robot. Due to the introduction of a customized 3D printed adapter, the overall assembly of the final robot is quick and the material costs are low. An analysis of related work has shown that many robots are either very expensive (several hundred Euro per robot) or intended for educational purposes. Our proposed robot can be a viable option where a configurable robot, with regard to e.g. different sensors, in a low price range is required or where a hexapod locomotion is preferred.

As a result of the mechanical analysis, a scaling law for friction yields loss of controllability with regard to friction of smaller models, as well as a better condition for survivability. A future task will be to investigate conditions of collaboration between robots to increase survivability by increasing cooperative functionality. Furthermore, we will investigate on an improved way to attach and switch sensors, which are glued to the funnel crenellation in the current prototype.

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