A Soft-Bodied Modular Reconfigurable Robotic System Composed of Interconnected Kilobots

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***Abstract*— We describe the Kilobot Soft Robot, a novel soft-bodied robot that is modular and reconfigurable. The Kilobot Soft Robot is realized by inter-connecting a group of miniature mobile modules, based on the commercially available Kilobot, through an elastic material. It moves and deforms fully autonomously. Each module executes a distributed algorithm that exploits only information that is locally obtained using omnidirectional, infrared based signaling. A series of experiments were conducted to validate the algorithm, investigating the ability of the robot to follow a predefined trajectory, to squeeze and extend its shape and to control its motion independently of the number of modules.**

I. INTRODUCTION

The Kilobot Soft Robot project aims to study potential synergies between two important robotic fields, swarm robotics and soft robotics. The former investigates how groups of robots self-organize to work together to perform a common task [1], [2]. The latter, which has been a particularly active research field in the last decade [3], [4], [5], [6], investigates robotic systems constructed from flexible materials, such as fluid, elastomers or gel. Soft-bodied robots are characterized by flexibility and adaptability in performing tasks and are generally safer to interact with than robots of conventional design [7]. The impact during a collision can be absorbed by the robot's flexible structure, making it less likely to cause damage [8], [9].

While soft-bodied robots of modular design have been already explored [10], the Kilobot Soft Robot introduces a less investigated alternative: A soft-bodied system that is both *modular* and *reconfigurable*, and may to some extent even be considered a robotic *swarm*. Applying the principles of swarm intelligence renders the robot more scalable, robust and flexible, with the potential to change its size and shape to cope with new and unknown situations [11].

We describe the design of and validation experiments with the Kilobot Soft Robot. Its modules are fully autonomous and mobile; they are extensions of the openly available Kilobot, an inexpensive mobile robot typically used in swarm robotics experiments [12], [13]. Each module can move using vibration motors, detect the distance to its neighbors, and communicate with them via omni-directional infrared signals. The modules of the Kilobot Soft Robot are mechanically coupled using elastic links (springs), which simplifies the estimation and control problem, and potentially makes the system more fault tolerant. The modules are arranged in a square lattice configuration (see Fig. 1). The dimension of the lattice can be manually reconfigured to suit different tasks. The aim is to control the motion and shape of the connected system through the combined actions of the individual Kilobots. For this purpose, we designed distributed algorithms to enable the Kilobot Soft Robot to follow a desired trajectory, to squeeze and extend its shape, and to control its motion independently from its size. Following this design, the Kilobot Soft Robot could be improved and built at a large scale, with possibly thousands of modules [14].

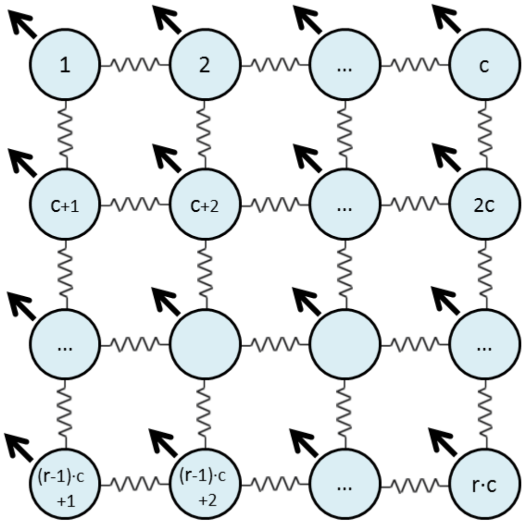

Fig. 1. The Kilobot Soft Robot consists of an $r \times c$ lattice configuration of Kilobot modules, interconnected with springs. The modules have unique identifiers, and are oriented in a common direction, indicated by the arrows.

II. THE KILOBOT SOFT ROBOT

The modules of the Kilobot Soft Robot, which are interconnected by springs, are arranged in an $r \times c$ square lattice configuration, as shown in Fig. 1, where r is the number of rows and c is the number of columns. The lattice size and, hence, the number of modules, can be manually modified before each trial or experiment thanks to the reconfigurability of the system. The modules are fully interchangeable; changes in the lattice configuration hence do not require reprogramming of the modules.

Each element of the lattice is a Kilobot, equipped with a holding structure [see Figure 2(a)] to mount custom-made springs of ca. 3.1 cm length and ca. 0.0425 g weight (averages across 20 samples). The Kilobot can estimate

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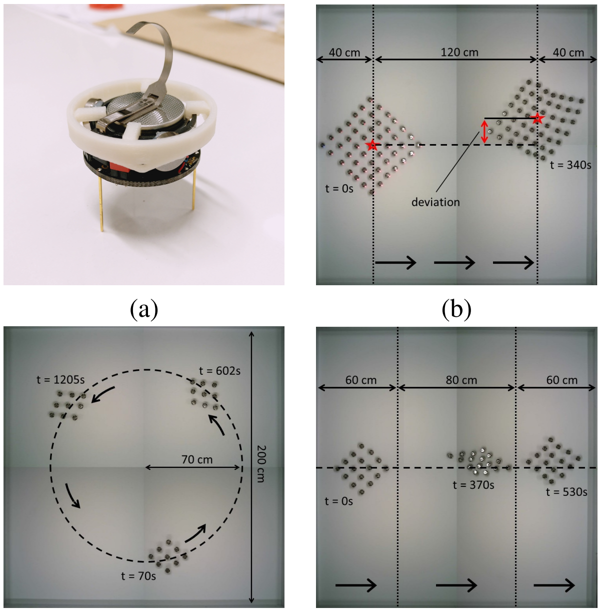

(a) (b)

(c) (d)

Fig. 2. Overview of the platform and results. (a) Each module is equipped with a 3-D printed ring-shaped holding structure to which custom-made springs can be attached. (b–d) Top view showing a typical trial for each of the three experiments. Multiple snapshots, taken at different times, are superimposed. Note that the springs are transparent, and thus not visible.

the distance from neighboring modules by transmitting and receiving 8 byte messages via omni-directional IR communication. It can turn left or right, or move forward, but is unable to rotate on the spot, or move backward. The mobility of the module is subject to restrictions due to the elastic links; this however helps the module to retain connectivity with its neighbors. As a result, the module can self-localize with respect to mobile neighbors, unlike [12], where the localization was performed with respect to stationary neighbors [12].

Each module executes an identical control algorithm. Every module, before deciding if and where to move, estimates its location relative to its neighbors. Kilobots are devoid of any sensors to detect the relative bearing between robots. Instead, they self-localize by relying on the neighbors' distances, estimated from the strength of infrared signals. We assume that each module knows the unique identifiers of its neighbors. In our experiments, this was realized by allocating the unique identifiers with a pre-defined pattern, shown in Fig. 1. Knowing its own identifier as well as the number of rows and columns of the lattice configuration, a module can determine its neighborhood. Once the relative positions are known, every module estimates the robot's local deformation from a desired global shape (i.e., shrunk, normal or extended lattice), and determines its motion direction to generate a corrective movement. Different corrective movements are implemented depending on the module's position on the boundary or interior of the lattice configuration.

III. EXPERIMENTS

We conducted a series of three experiments, each one investigating a different capability of the Kilobot Soft Robot: (i) the motion accuracy as a function of robot size (up to 49 modules), (ii) the ability to follow a curved reference trajectory, and (iii) the ability to control the deformation of its body while in motion. The experimental set up was based on the Augmented Reality for Kilobots (ARK) technology [15]. ARK comprises an array of overhead cameras for real-time position tracking, a base control station, and an array of overhead transmitters to send in real-time messages to every Kilobot. In all experiments, ARK is used to record the positions of the modules for post-analysis.

The aim of the first experiment [Fig. 2(b)] is to evaluate if a relationship exists between the Kilobot Soft Robot size (i.e., the number of modules) and the accuracy of movement, when tasked to move straight while retaining its square lattice shape. The Kilobot Soft Robot is controlled in an open-loop setting, without external feedback on the followed trajectory. We observed how a large number of interconnected Kilobots compensates the individual inaccuracies on the movements due to the collective cooperation. The motion of the Kilobot Soft Robot becomes more accurate as the number of modules, and hence its modular resolution, increases.

The second experiment [Fig. 2(c)] shows how the Kilobot Soft Robot is able to follow a predefined curved path while retaining its square lattice shape. The robot was not directly provided with the path, but rather with feedback by the ARK system whether the desired path was towards the left, or towards the right. This feedback was only provided to a single module, located at the robot's front.

The last experiment [Fig. 2(d)] examines the performance of the Kilobot Soft Robot when instructed to deform its shape (shrunk or extended in lattice) while following a predefined path. The ARK system was used to inform the robot when the changes in deformation are to be triggered. The results show that the robot could successfully shrink its body and then restore its original shape.

IV. CONCLUSIONS

We presented the Kilobot Soft Robot, a novel concept for a modular soft-bodied robot. The Kilobot Soft Robot is composed of simple mobile modules, Kilobots, which are interconnected by springs to create a deformable 2-D lattice structure. The modules can be manually reconfigured to create lattices of arbitrarily dimensions. Fully distributed algorithms were designed that allow the Kilobot Soft Robot to move in a planar environment, while controlling its shape. Experiments with up to 49 physical modules were conducted to validate the properties of the system (scalability). The experimental results show how the robot motion accuracy increases with the number of modules constituting the robot.

To the best of our knowledge, the Kilobot Soft Robot is the biggest soft-bodied modular robot to date made of fully autonomous modules. The findings of this study raise the question whether soft connections are superior to rigid ones, making it possible to scale up the number of modules in reconfigurable robots that move across the ground.

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