# Beanbag Robotics: Robotic Swarms with 1-DoF Units

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**Abstract.** Robotic swarm behavior is usually demonstrated using groups of robots, in which each robot in the swarm must possess full mobile capabilities, including the ability to control both forward and reverse motion as well as directional steering. Such requirements place severe constraints on the cost and size of the individual robots (swarmers), limiting the number of units and constraining the overall minimal size of a swarm. Here we show that similarly-complex swarm behavior can be achieved using much simpler individual swarmers. These possess significantly fewer controllable degrees of freedom, namely the ability to move forward at different velocities. We demonstrate how the interaction between different units then causes the entire swarm to obtain maneuverability unavailable at the individual level. These results may open the door to fabrication of simpler and smaller units for swarms allowing significantly larger numbers of units and smaller overall swarm footprints.
**Key words:** Swarm Intelligence, Evolutionary Robotics, Collective Behaviors, Self-Organization, Liquid Robotics, Artificial Life, Navigation

## 1 Introduction

Social insects, schools of fish and flocking birds often exhibit cooperative swarming behavior that enables complex tasks that individuals (*swarmers*) cannot manage separately. The system as a whole is said to accomplish more than the sum of its parts and to be scalable, robust and fault-redundant [1]. These observations have inspired studies in the field of swarm intelligence that seek to demonstrate similar properties in synthetic swarms [2, 3]. Most reported demonstrations of robotic swarms use groups of individual swarmers already in possession of high degrees of locomotive freedom. This complexity leads to several consequences including higher costs, more possible points of failure and fewer redundancies and places severe constraints on the minimal size of individual swarmers and consequently on the size of the swarm. We suggest that complete navigational control can be attained using much simpler units, that have only the ability to control the speed of their noisy forward locomotion, constrained in a

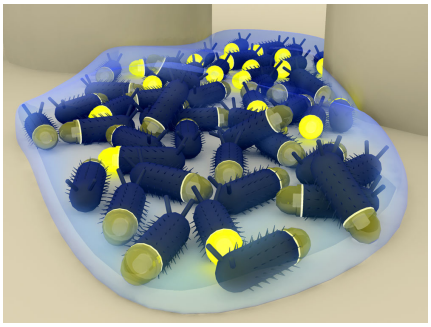


**Fig. 1.** Concept of a robotic system built of swarmers and a passive membrane, changing its shape to get through the gap in the background.

flexible membrane (Fig. 1). We use evolutionary computation methods to demonstrate how a swarm of these simple devices can accomplish behaviors equivalent to those demonstrated by swarms composed of fully controllable individuals.

**Outline** In this paper, we will first present a concept of simple swarmers (Sec. 2). We outline our principles of swarmer simulation (Sec. 3) and demonstrate first evolved behaviors (Sec. 5) in two standard experiments (Sec. 4). Following, we call attention to problems concerning the swarm and present a passive membrane as solution. We will then present the results of the same experiments performed with the membrane added (Sec. 6), and present reliability statistics. Finally, we present two physical swarmer implementations (Sec. 7) with the potential ability to be built at a very small scale.

## 2 Swarmer Design

**Morphology, Restricted Locomotion and Steering Options** The swarmer morphology is kept very simple in our experiments: Every swarmer's body is elliptical in shape (Fig. 2). In every experiment, the sensor area is triangular, beginning at a swarmer's front. The sensor height is about $20 \cdot x$, the sensor width about $10 \cdot x$, where $x$ is a swarmer's length (arbitrary units). A swarmer is equipped with a tail-light that may be switched on or off, with other swarmers able to sense its state. It only has the ability to locomote forward and is unable to control its orientation. When it moves forward, some random noise up to 30 degrees is added to its orientation, leading to stochastic movement trajectories.

**Synthesized Controllers** In the experiments below, we synthesize the controllers using evolutionary algorithms [4, 5]. We evolve [6] the weights of a recurrent neural net [7, 8] that controls locomotion speed and the tail-light in response

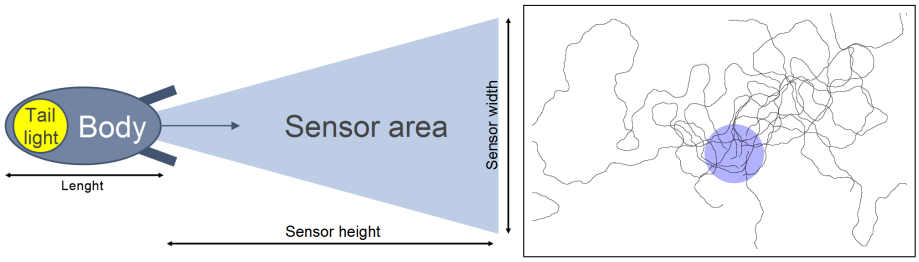



**Fig. 2. Left:** Individual swarmer architecture. The arrow represents the movement direction. **Right:** 10 sample trajectories by swarmers starting from the blue area.

to input from the frontal sensor(s). All swarmers have identically evolved controllers. Fitness was determined as a function of an overall swarm behavior with regards to reaching a specific goal.

## 3 Simulation Principle

Simulations consist of a number of simulation steps carried out iteratively. In one step, every swarmer moves a distance defined by its speed towards the direction in which it is currently oriented. In addition to the swarmers, the world also contains two types of immobile objects. The first type constitutes obstacles that are impenetrable to the swarmers, while the second is penetrable to the swarmers, as if drawn underneath them (examples: light sources, nest objects). Objects that swarmers can sense must be visible to them, implying that they must not be entirely covered by another object or swarmer. Some experiments contained interaction with an additional, elastic passive membrane, which will be introduced in Sec. 6. Being made of a closed chain of 50 links, the membrane simulation uses kinematic relaxation methods [9]. The swarmers can apply forces to every single link. In return, the entire membrane applies reaction forces to swarmers while contracting after elastic expansion. As a result, the membrane can move, expand and change its shape.

## 4 Experiment Setups

During all experiments, the swarmers were given one of the following two tasks: Reaching a light source, which makes it necessary for the swarm to navigate and avoid obstacles, or food foraging, which adds the challenge of collective decision making, because there are two possible locomotion goals: the food, and the nest.

**Light Search** Our first goal was to create swarmers capable of reaching a light source. A swarmer is equipped with a single brightness sensor on its front. A swarmer's controller has four inner neurons, one input neuron receiving the

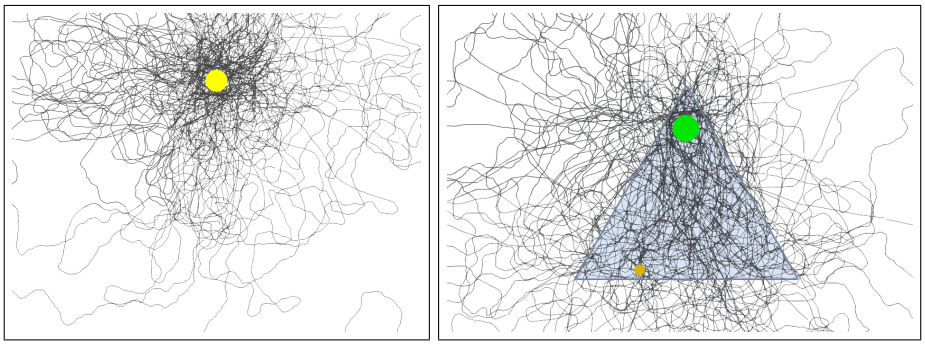


**Fig. 3. Left:** Traces of swarmers evolved to stay close to a light source (yellow). **Right:** Traces of swarmers evolved to collect food and bring it back to their nest (green). The food (orange) re-appears at bottom of the triangular area marked blue.

brightness value, and two output neurons controlling the forward movement speed and tail-light. The brightness stimulus given to the input neuron increases quadratic: The nearer, the higher gets the stimulus. We assumed that a swarmer needs to gather energy from light sources to keep up an internal energy level: If it does not see the light source soon after starting, the energy level will gradually decrease to zero, so it will stop. If it sees the light source, it can gather energy from it – the closer, the more. In our fitness function $f_1$ (eqn. 1), $e$ represents the gathered energy, $d$ the distance to the light source (each measured per swarmer simulation end) and $n$ represents the number of individuals in the swarm.

$$f_1 = \sum_{\text{swarm}} \left( \frac{e - d}{n} \right) \tag{1}$$

**Food Foraging** In this experiment, food is collected by touching, and delivered to the nest by touching the nest afterwards. When a food item is collected by a swarmer, a new one appears at another (random) location, so that the number of food items is not limited by the environment. In the fitness function $f_2$ for this experiment (eqn. 2), $f$ represents the number of food items delivered to the nest by an individual swarmer, measured at the end of the simulation.

$$f_2 = \sum_{\text{swarm}} f \tag{2}$$

The controller was slightly modified: It contains four input neurons for sensing swarmer tail-lights, food, the nest and whether the individual swarmer had food loaded. The stimuli for the input neurons for food, nest and tail-lights were generated analogously to the light stimuli in the first experiment. Furthermore, we increased the number of inner neurons to fice.

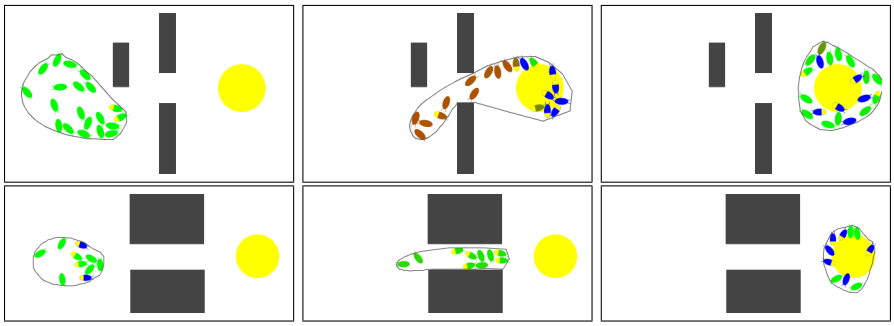


**Fig. 4.** Frames of the light searching swarm in a membrane with different obstacle layouts. The swarmer colors represent the energy state of the swarmers: Blue means that they are fully charged, black means that they have no energy, and their color gradually changes from green to red while discharging. A yellow tail indicates a tail-light turned on. The yellow object represents the light source, dark objects are obstacles.

## 5 Experiments and Problems with Free Swarmers

In the light source experiment, the swarmers evolved a behavior that made them speed up when a light source was visible and slow down otherwise. The overall behavior of the swarmers was an oscillating locomotion around the light source (Fig. 3, left part). In the food foraging, too, the swarmers evolved behavior to solve that problem (Fig. 3, right part) by accelerating and getting slower at appropriate points in time. So in general, the simple swarmers were capable of completing their tasks in both cases – but there remains a problem that needs to be addressed: Individual swarmers can easily get lost if they move too far away from the destination to sense it, or if it is occluded by obstacles.

## 6 Experiments with Swarmers in a Passive Membrane

A solution to the problem mentioned above is to create a passive, elastic membrane around a group of swarmers. The swarmers can apply forces to the membrane, and the resulting reaction forces are then applied to the swarmers in turn. The overall swarm movement direction is then the direction in which the majority of swarmers apply a force. In subsequent sections, we present a comparison of the light search (this time with obstacles) and the food search – both with swarmers in a membrane, and free swarmers.

**Light Search** The swarmers had to get through a narrow gap to reach the target light source, which was in addition partly occluded by another obstacle. The swarm without the membrane did not evolve any successful behavior for this task (see evolution statistics in fig. 5). Although each swarmer is as simple as described, the swarm with membrane evolved a behavior which allowed it to perform directed locomotion, avoid the obstacle, morph to get through the gap

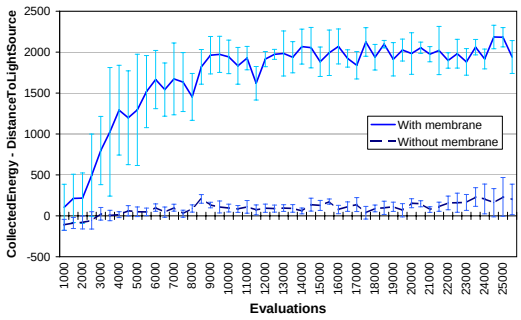



**Fig. 5.** Light search fitness plotted by number of evaluations. The error bars represent the standard deviation.

and then reach and stay on the light source (Fig. 4). The controller of the light-seeking swarm enclosed in a membrane did not need to evolve dynamics, even though it had the opportunity. The more light a single swarmer sees, the faster it moves, and if the sensed brightness surpasses a certain treshold, a swarmer switches on its tail-light. This simple behavior implies that swarmers that are able to see the goal accelerate in the direction of the goal and propagate the signal to attract other swarmers that are not positioned to directly see the goal.

**Food Foraging** This experiment was also repeated using the membrane-enclosed swarm. However, when looking at the evolution statistics (Fig. 7, left pane) the swarm without membrane seemed to be more efficient. The reasons for this effect are the following: When not contained in a membrane, individual swarmers move much faster, so that when all swarmers are in the right region, they can collect more food per time than the swarmers in the membrane. The food foraging behavior of the membrane-enclosed swarm was to collect several food items at a time and then return to the nest to deposit all of them simultaneously (Fig. 6), which is slower. But as free swarmers get lost over time, the swarm without membrane gradually loses its efficiency, while the swarm with membrane showed more robustness and reliability. The behavior of the membrane-enclosed swarm seems to follow the following rules: Whenever a swarmer sees a food object, a nest or swarmer tail-light, it accelerates. Whenever a swarmer sees a food object or another swarmer's tail-light, it switches on its own tail-light. However, seeing a nest does not cause a swarmer to switch on its tail-light. The result is an oscillating locomotion between the nest and food objects, where the swarmers are more likely to go to the food because of their tail-lights, which they only switch on when they see food in order to attract others.

In all evolutionary runs (regardless of the specific goal) the swarmers, if put into a membrane, evolved controllers which showed the capability to locomote in an arbitrary direction as a collective behavior. In addition, no swarm ever got lost during our experiments. Without membrane, both light search and food foraging experiments were either impossible or unreliable over long time.

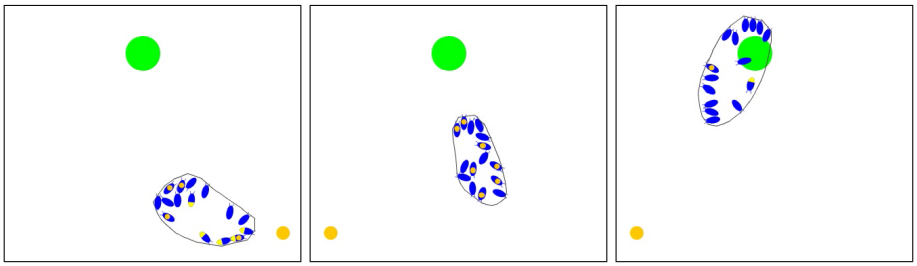


**Fig. 6.** Frames of the food collecting swarm in a membrane. The green object is the nest, the smaller orange objects are food objects. The food on the back of the swarmers is shown if they carry any. A yellow tail marks a tail-light turned on.

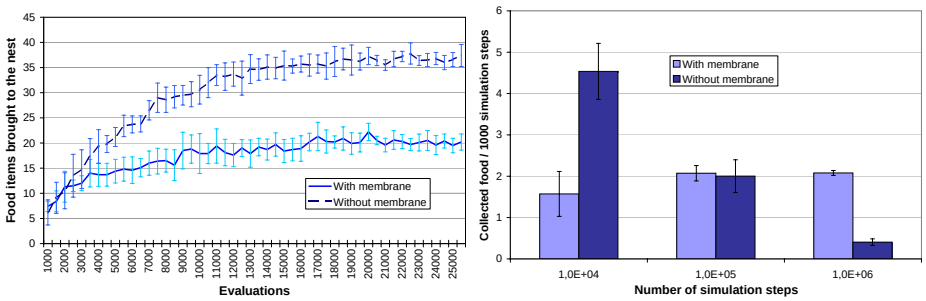



**Fig. 7. Left:** Food search fitness plotted by number of evaluations. **Right:** Performance of the evolved swarm with and without a membrane over longer periods of simulation. Error bars represent the standard deviation.

## 7 Physical Implementation

The simplified requirement of only forward, unsteerable motion, allows the consideration of much simpler robot designs. For example, simple vibratory actuation combined with non-symmetrical (directional) friction, can provide such noisy forward motion. A physical prototype imitating this behavior can be seen in fig. 8, where thorns create the directed friction and a pager motor provides vibration. We suggest that this simplified behavior is more appropriate for microfabrication than traditional robot designs. Another prototype capable of simple forward motion [10] can also be seen in fig. 8.

## 8 Conclusions and Future Work

We presented a simple swarmer that is only capable of noisy forward locomotion. Using a passive elastic membrane, we showed that this simple behavior can be channeled to achieve a variety of complex behaviors that are traditionally accomplished using significantly more complex individual swarmers. We showed a robotic system that is *highly redundant*. It is also *morphable* and capable of

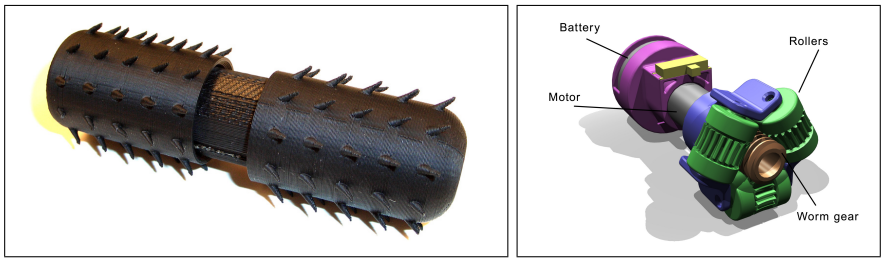



**Fig. 8. Left:** Implementation of the directional friction approach. The thorns that cover the surface cause directed friction, while one of the two parts vibrates along the axis of a swarmer. **Right:** A more traditional approach. A pager motor turns a worm gear that drives three rollers.

*robust*, relatively *complex* behavior. Furthermore, it is *variable in size* by two factors (the size of every swarmer and the number of swarmers in the membrane), and capable of *directed locomotion* even though the individuals are not. The agility of locomotion achieved by an artificial robotic swarm demonstrated in this paper, opens the door to a concept of "beanbag" robotics: Simple swarmers in a membrane. Ultimately, a robotic system consisting of large numbers of very small swarmers in a membrane could behave almost like a liquid, able to freely change its overall shape while moving in any desired direction.

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