The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

A biomimetic honeybee robot for the analysis of the honeybee dance communication system

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***Abstract*— A new biomimetic honeybee robot capable of dancing and mimicking all known signals in the honeybee dance communication system has been built. This paper describes the hard- and software design of the first honeybee robot with computer vision. The robot can robustly recognize obstacles and react on imminent collisions.**

I. INTRODUCTION

We are studying the idea of using a honeybee robot to investigate the role of various stimuli and behaviours in the honeybee dance ([20]). In this paper we present our current prototype and the design parts that make this robot unique in the time line of previous honeybee robots. The honeybee dance communication system gained much attention throughout the last century when Karl von Frisch's work on honeybee behaviour was awarded the Nobel prize. Although in school books the mystery of the dancing honeybees seems to be solved there is still an ongoing controversy within the honeybee research community ([11], [36]) - some researchers question the characterization of the honeybee dance as a symbolic communication system. Intriguingly, one can observe high correlations of dance properties and field site location properties. Thus, humans can easily decode a waggle dance by looking at it but it is still unclear how the dance followers can - or even if they - understand it. A dancing honeybee performs the so called waggle dance on the comb surface after returning from a valuable location in the fields. This might be a food source but also a new nest site or water source as well. For the human observer the dance is clearly differentiable from any other behaviour. The dancer moves forward in a rather straight line shaking her body from side to side. This so called waggle run is succeeded by alternating left and right turns, back to the approximate beginning of the waggle run. This is performed repeatedly several times interrupted only occasionally by a behaviour called trophallaxis, in which the dancer bee offers food samples to follower bees (see [12] or [8] for a detailed review of the honeybee dance). The angle of the waggle run with respect to gravity highly correlates with the angle of the food source with respect to the sun's azimuth. If the food source on an outbound flight is located directly towards the sun, the waggle runs point upwards on the vertical comb. The distance to the feeding source correlates with the length or duration of the waggle run. Follower bees have to "read" this angle and duration in the darkness of the hive and translate it to the direction and distance of the goal in the field. Many stimuli have been hypothesized to be involved in the communication process but could not be proven to be signals. Quite recently, the context of dance communication has been made an important key to understanding ([13]).

A. A Honeybee Robot for Understanding the Bee Dance

Using a robot for the production of an artificial honeybee dance one is able to individually control the signals being emitted. One can, e.g. use only the wing oscillations without wagging the body from side to side. We aim to study the effects of all signal combinations to learn about the importance and information content of the signals. The idea of building animal robots to analyze behaviour is not entirely new ([14], [23]). In the late 1980s a robot quite similar to the presented one was built ([20]). In a previous work we propose a light weight prototype of a honeybee robot ([15]). Since in both works there were no clear results in recruiting follower bees, we extend the robot's design with recently published putative signals, camera sensors and precise motion data obtained from highspeed dance recordings. We also hypothesize the communication system to be two-way. From an engineer's point of view, a communication protocol is more robust when using a channel back to the sender to synchronize, acknowledge or tune the reception of messages. It might be possible, yet not reported, that follower bees also emit signals towards the dancer. One example might be the so called stop sounds emitted by tremble dancers and follower bees. These vibrations are hypothesized to elicit trophallaxis ([6]) or to serve as a negative feedback for dances ([22]). We might even think of body contacts as a signal that is used to tune the dance path for the bees that through these body contacts show that they are ready to receive information. The camera sensors that enable the robot to react on the environment might be the key not only to the acceptance of the robot but to the recruitment of followers.

To successfully recruit forager bees using a robot a number of prerequisites have to be met. First of all the robot has to be accepted as a nestmate. Researchers hypothesize a number of chemicals involved in this process ([3], [2]) but also describe a temperature rise of bees under examination of guards ([30]). Since bees differentiate between the cuticular compounds of bees of different classes (drones, food storers, foragers, queen attenders, [10]), the robot might have to be disguised as a forager bee as well. After blending in, attention has to be aroused towards the dance. After potential recruits recognized the existence of a dance the following behaviour has to be incited and kept up. In natural dances

This work was supported by the German Research Foundation.

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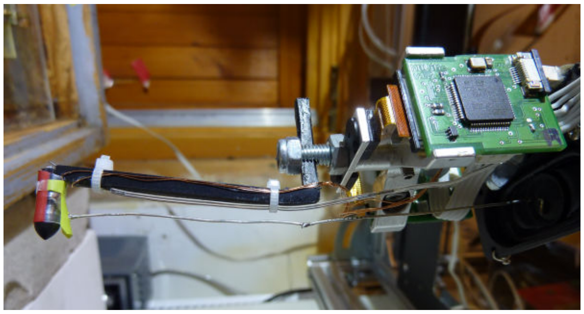

Fig. 1. Closeup of the central rod at whose end the robotical bee body is attached. It integrates a temperature sensor and a heating resistor. A small canula is used to deliver small amounts of sugar solution to the body's head. The wings are driven by a small speaker. Two camera modules are fixed to the central rod such that they are looking down to each side of the body.

followers stay in close contact to the dancer, seem to keep a particular relative angle towards the dancer's body and are most likely to receive trophallaxis. That means the robot has to allow the particular following movements and might even have to react on squeaking signals ([5]) of the followers to stop and initiate trophallaxis. The final recruitment, i.e. the follower bees fly out to seek for the new feeding site, is our main goal. The validation of the flown route in the field is being done by harmonic radar techniques (see [25], [18]) in collaboration with the group of Prof. Randolf Menzel. Yet it is not clear how these abstract stages fit the bees' behavioural structure.

B. Signals in the Honeybee Dance

The putative signals in the dance communication system are all signals going from the dancer to the follower bee(s). The information being transmitted is threefold: 1) the angle to the food source (i.e. the angle with respect to gravity) 2) the distance to the feeder (i.e. the length or duration of the waggle run) and 3) the desireability of the source (i.e. the "liveliness" and the number of waggle cycles per dance) ([8]). But these direct parameters might be transmitted only after some general signals of arousal are emitted.

1) Odors and the Waggle Scent: The honeybee dance research community agrees on only one fact: The use of odor information in the recruitment process. Honeybees give samples of what they had been collecting in the fields by reurgitating drops of the previously collected solution - a behaviour called trophallaxis - or by presenting the pollen and scents brought into the hive on their body ([8]). Recently it has been shown that there might be special dance pheromones involved as well ([34]). Bees that were trained to forage on a scented artificial feeder can be incited to forage by just spraying the scent into the hive ([24]). Therefore the use of odor coupled sugar solution must be avoided in the experiments. The recognition of nestmates relies crucially on odor information ([3], [2]). Honeybees exhibit a special sensitivity towards wax compounds found in the comb and the cuticula ([9], [10]).

2) Antenna-to-Body Contacts: Antennal contacts of the follower bees to the dancer's body are most likely to contain information. By reading the deflection angle of the antennae (or the temporal dynamics), bees might be able to compute the dancer's orientation angle ([1], [26]).

3) Laminar and Oscillating Air currents: It is known that during the waggle portion of the dance the dancer is oscillating its wings in pulses of approx. 280 Hz ([7], [21]). These oscillations are the driver of oscillating air currents at the rim of the wings and laminar air flows around the bee body directing rearwards (called jet streams, [31], [19]). The tuning of the Johnston organ inside the pedicels of the antennae towards frequencies of around 300 Hz ([35]) is a strong hint these stimuli might be received and used for the detection of a waggle.

4) Substrate Borne Vibrations: The wing oscillations generated by the flight muscles located in the thorax are fed into the comb through the legs, too. Bees might be able to recognize the comb vibrations over a distance of several hexagons ([32], [27], [33]). This might serve as an attraction signal.

5) Temperature Rise: Dancing bees exhibit a higher temperature that is produced by their flight muscles that generate the wing vibrations ([4], [29]). A temperature "behaviour" also might play a key role in disguising the robot ([30]).

II. SYSTEM DESIGN AND HIVE SETUP

A. Mechanical Setup

Our honeybee robot is based on a Roland plotter (DXY-1300) as the x/y positioning unit. We removed the built-in electronics completely and built our own (see II-C). We added a third stepper motor for the orientation of the bee robot to the pen carriage and a fourth stepper for the trophallaxis machinery. A window was cut out of the plotter's surface to make the robotic dance easily observable from behind the robot. The whole construction was fitted into an aluminium frame for higher stability. This frame can be pitched to align the robot's motion plane to the comb surface. A metal rod is fixed onto the third motor that carries the bee body, the cameras and all signal units. The camera modules are affixed such that the two eyes are looking down on each of the body's sides. The body itself is attached to the metal rod using a plastic elbow. The motion of a dancing bee during the waggle phase has a rotational component and a lateral translation. The elbow element is used to excenter the body such that only the third motor can generate the waggle motion. Although the rotational amplitude is now fixed to the translational amplitude the system gains mechanical stability compared to a waggle that is produced by all three motors.

B. Stepper Motors and Stepper Controls

We use three hybrid synchronous stepper motors (two-phase) for the motion generation of the robot. The x/y steppers and the orientation motor have an angular resolution of 0.9° and 1.8° per step, respectively. This resolution is increased by the use of micro step motor controls. A fourth stepper motor is used for the trophallaxis. The stepper motor controls generate the two-phase step cycles for the 4 motors used. The microstep motor controls generate microsteps as

$\frac{1}{16}$ of a unit step. Using these stepper controls the trajectories are made very smooth.

C. Hardware / Electronics

The electronics for the robot have been designed completely new. The main board comprises: a voltage supply, stepper motor control units, usb interface, a relay board and the main processor. The power supply is fed 16 V (for the motors) and it provides 5 V for the USB interface board and 3.3 V for the main processor and the cameras. The USB interface is used for the communication of the main processor and the connected PC. The main processor, an Atmel ATXmega128, based on an extended 8-bit AVR architecture, is responsible for the communication with the cameras, the PC and the actuators. This processor is easy to program and has a lot of nice features like 4-channel DMA, eight-channel event system, 12 bit ADCs, double buffering, etc.

D. Signal Generators

For the wing oscillations we use a small speaker that is driven by rectangular signals of a given carrier frequency and pulse rate. The Trophallaxis is done by squeezing drops of sugar water out of a small flexible tube using a miniature stepper motor. Using this mechanism we can present tiny amounts of food samples at the head of the bee body (see Figure 1). The step frequency for a specific amount of sugar solution was calibrated by measuring the size of the drop optically after a unit period of time. Temperatures of around 40 $? \circ C$ are produced by a small resistor in the thorax of the bee body. We can measure the temperature using a small temperature sensor (DS18S20).

E. Optical Sensors

Since it is advised not to overrun potential followers to avoid aggressive behaviours, we use two camera modules for the detection of obstacles. This system has very low latency and enables the robot to immediately react on imminent collisions. To simplify and speed up the recognition we lighten the back of the dance floor with red light (720 nm) using an LED array. Bees standing on the comb can be recognized in the camera image by the shadow they cast. The modules are based on an Atmel ATMega8 microcontroller. All object recognition tasks are done on this controller. The results are reported back to the main processor of the robot via a serial connection. Image regions of only 80 px by 30 px size are evaluated per frame. Seven so called Sensor Regions of Interest (SROIs) can be defined dynamically inside this ROI using the software described below.

F. Software

The software for the system can be structured in three layers: a) camera, b) robot, c) PC. The cameras' firmware basically consists of a serial communication protocol, the camera configuration machinery (read and write registers, set ROI and SROIs) and the image evaluation algorithm. The mean pixel intensity of a SROI pixel patch is computed and compared to a preset threshold value. If the pixel mean stays below the threshold the SROI region is considered obstructed. The size of the SROIs can be set to up to 100 square pixels each. The modules report only one byte to the main processor where one bit is used to identify the module and the 7 remaining bits encode the sensor region's occupancy. The software running on the PC is used for configuration purposes, visualizes the camera's sensory data and is used to control the robot. The GUI is partitioned in various tabs. One is used to set the location of an artificial feeder in the field. The direction and distance to this location is transformed into the dance parameters waggle angle and waggle duration. The angle of the feeder has to be formulated with respect to the sun's azimuth which can be computed for any location and time. The distance is translated into a waggle duration. We use a quadratic fit of the data from [8] to generate a the waggle duration as a function of any distance. Other dance parameters can be set to change the shape of the dance (see Figure 3). A simulator was programmed to test different reactive behaviours, like slowing down, evasions, etc. The integration of these two layers is done by the robot's firmware. It is used to control the actuators in dance and configuration mode. It handles the communication channels with the cameras and the PC and uses the sensory results for the robotic dance.

Fig. 2. Experimental setup. The observation hive has four windows we can open to insert the bee sized body of the robot. The body can be moved with an x/y positioner that is mounted vertically in an aluminium frame.

1) Dance Model: A parametric dance model was created to generate artificial dance trajectories that resemble natural dances. Therefor over 80 dances containing about 700 waggle and return runs were recorded to highspeed video files, tracked using a custom program ([16]) and evaluated ([17])

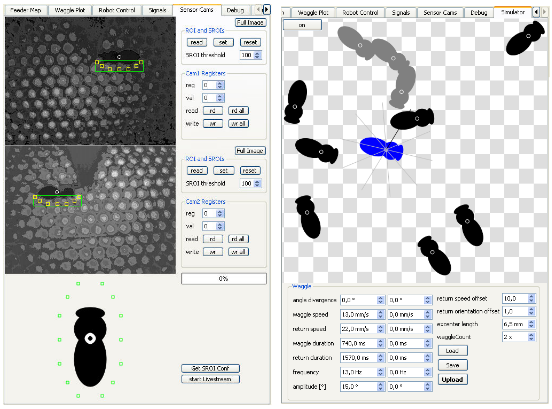

Fig. 3. Screenshot of the camera configuration panel (left) and the dance simulator (right) of the GUI. In the camera panel the images of both cameras are displayed. The location of the ROI and SROIs can be set with a few mouse clicks. The sensory data is visualized schematically in real-time.

to extract a set of 11 parameters that describe an arbitrary honeybee dance.

G. Hive Setup

We use a custom built four-frame observation hive whose comb frames are made with plastic glass plates to inhibit the bees to populate the backside of the frame. The frame nearest to the hive exit (the one that is danced on) is backlighted using red light LEDs. We are using this setup to simplify the detection of bees standing in the way of the robot (see II-E). The hive can be opened from the front side to give access to the dance floor. The hive is used indoors under red illumination to minimize the disturbance of the colony. Honeybees have no receptors tuned to red light and therefore perceive only very small amounts of red light ([28]). A small tube of 25 mm diameter is used to connect the hive entrance with the outside through a hole in the window. A highspeed camera system (Basler A602f) is used to observe the experiments with the bee robot. This system is able to record VGA frames at 100 fps continuously. The hive is temperature controlled. Since we have to open the glass window to gain access the comb surface, the hive will cool down. To reduce this effect, the room is heated up to 28 degrees.

III. RESULTS

The robot can be configured comfortably using a graphical user interface. The coordinates of the experiment's location can be set and the azimuth for the any time can be computed. The dance angle is set accordingly - the dance shape can be defined by a set of parameters and viewed as a dance simulation with obstacle recognition. All functions of the robot and the sensor cameras can be tested and configured through the GUI. Parameter sets can be saved to files and loaded again. The current status of the robot is continuously displayed. The robot can be manually moved by the use of the mouse or a keypad. The wing oscillations, the trophallaxis and the temperature signals can be configured by a set of parameters. The two sensor camera modules can be configured easily. In comparison to the previous honeybee robots ([20], [15]) we have added a more natural dance model, that is supported by statistics of aproximately 1000 waggle runs. We use special scents reported recently ([34]) and reproduce jet air flows that were not implemented on previous robots.

A. Motion

The robot is able to move in a cartesian coordinate system at a spatial and temporal resolution of 0.1 mm and 1 ms, respectively. Maximum motion velocity is 200 mm / s. The angular resolution is 0.12°. The maximum amplitude is 40° (peak to peak) and using an excenter rod of 15 mm size ca. 10 mm - more than real bees do. Unlike our previous prototypes the distance of the bee body to the comb surface remains constant - given a perfectly planar comb surface.

1) Dance Trajectories: The dance model can reproduce natural trajectories. Figure 4 shows a plot of a robotical dance and the trajectory of a real bee's dance.

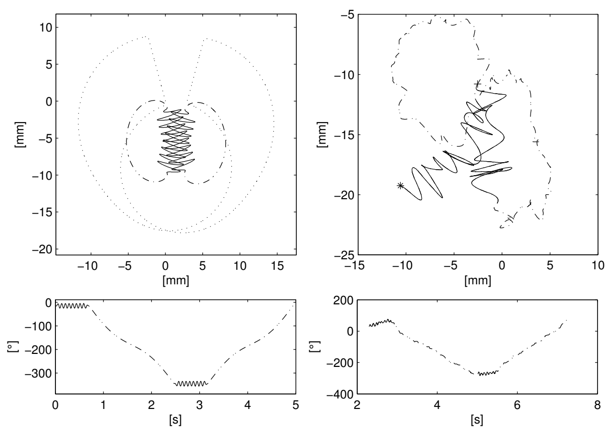

Fig. 4. Comparison of the robotical dance model to a real dance. The top left plot shows the planar positions of the bee body. Dash-dotted lines denote the return run, solid lines the waggle portion of the dance. The dotted line shows the path the x/y steppers describe. The waggle is entirely produced by the third stepper motor, whose activity is shown in the lower left plot. The right plot column shows a waggle dance tracked from highspeed recordings split into the body's center positions (top) and the orientation angle (bottom). The artificial trajectory represents the average motion of honeybee dances.

2) Obstacle Avoidance: Depending on the light conditions we reach framerates of 70 fps. Severe collisions in the return run can be avoided with this system. At this time the sensory data of the camera modules are used to slow down the robot before an imminent collision. The dance shape is not altered, i.e. there are no evasive maneuvers being undertaken, only the motion speeds are multiplied by some fraction of 1. This decreases the impact energy and we observe less agressive behaviour towards the robot. The obstacle avoidance is not used during the waggle run. This might be tolerable when shoving other bees at the robot's head, because this is what we observe real dancers doing ([15]). On the other hand, the obstacles at the robot's sides are hit in a waggle with high velocities and high force. Since the framerate and the exposure time do not allow the use of the sensor in the waggle phase we are currently improving the camera modules (see IV-B).

B. Signals

All known stimuli can be reproduced except comb vibrations.

1) Wing Oscillations: We tested different kinds of actuators for the generation of wing oscillations: a custom-made solenoid, a DC motor and a speaker. The speakers are found to meet best the requirements in frequency and amplitude but might be bulky. The solenoid can be oscillated at all feasible frequencies and is less heavy than the speaker but is not be able to produce an amplitude of 0.2 mm (peak to peak displacement of the wing tips). The small DC motor, used in mobile phones for the vibration alarm, can produce big amplitudes and is the smalles actor but cannot reach frequencies of over 260 Hz. The wing oscillations can be synchronized with the waggle oscillation, i.e. the pulse rate is set equal to the waggle frequency and the pulses' location on the waggle trajectory can be set freely using an offset time after waggle start.

2) Trophallaxis: The trophallaxis motor squeezes little drops of sugar water out of a flexible canula. It can be used to present food sample drops of 0.2 mm^3 size at the robot's head. This is done in the waggle mode of the robot after a variable number of waggle runs. The robot is stopped and a drop is presented to the follower bees. After a defineable number of seconds the dance is continued.

3) Heat: The thorax part of the bee body can be heated up to 42 °C and maintained using a proportional derivative controller.

Fig. 5. Picture of the robot while dancing on the comb surface.

C. Validation Experiments

Preliminary experiments have been conducted to test a) the acceptance of the robot and b) the influence of any experimental action on the behaviour of the hive. To quantify the general effect of the robot we measure the optical flow in the area around the robot's body and compare it to the amount of motion of the same area from a recording 10 min prior to the experiment. The effect of opening the hive and using red lighting was also measured using this method. To rate the acceptance of the robot we review highspeed video recordings frame by frame and count the amount of antennal contacts and compare these values to a reference count obtained from recordings of natural behaviour. Opening the hive leads to a temperature drop that results in clumping of bees in the area that was exposed to the outside and makes it nearly impossible to move the robot on the comb surface. After heating the laboratory up to 28 - 30 ° C we observe no clumping. Also the lighting with red light had no significant effect. Different kinds of body materials (plastic foam, foam wrapped in beeswax, PVC, silicon) were put into the hive two days prior to the experiments to absorb the scent of the hive. Then the bodies were fixed to the robot and moved (without dancing) manually inside the hive at different motion velocities. We found that wax or plastic (PVC) bodies were not attacked and similarly often examined as the reference count. Silicon bodies might have had a repellent smell, we found stings on the body after 10 minutes of moving around. We also tried to use real bees (anaesthesized or dead). Their advantage is the flexiblity of the abdomen which makes the dance look even more smoothly and the overall similarity in shape, texture and smell. The preparation time of almost 30 min (or even more if an anesthaetic is used) makes the use of real bees not very feasible. Dead bees are attacked after one to three hours from the time being killed. Also the use of a non-smelling glue is important. The heat that is produced by the robot leads to an increased evaporation of the glue and aggressive behaviours of the surrounding bees can be observed - a loud and high pitched sound is emitted. We designed holders for every part of the robot's central rod to reduce the amount of glue to a minimum. The bodies that were not attacked right away were used for short waggle dances to test for attraction. We observed bees approaching the robot, making short antennal contact, turning away and either leave the vicinity of the robot or do the touching repeatedly. We have not yet observed a bee following the robot for more than a waggle cycle (i.e. one waggle run and a subsequent return run), although some bees stayed over several minutes close to the robot touching it repeatedly whenever it came across, some showing an extended proboscis (tubular feeding and sucking organ) towards the head of the bee robot, even when the syringe we use to present food samples was filled with water only). Also we learned that the custom frames we built to prevent the bee from populating one side of the comb were undermined. The bees lifted the wax comb from the plastic slide and after two weeks had established the normal two-sides occupancy. Fortunately, this had no severe effect on the obstacle recognition algorithm.

IV. CONCLUSIONS AND FUTURE WORK

A. Conclusions

Our robot integrates the features of previous prototypes and even extends them. The robot is able to reproduce very realistic dances and reacts on its environment. First experiments have been conducted to test the dance motion and the acceptance of different materials used to model the robotical bee body. This robot enables biologists to conduct complex biological experiments on the honeybee dance communication system.

B. Future Work

Clearly, the camouflage of the robot has to be improved in the next season. We plan to build injection moulds to build robot bodies that integrate small odor reservoirs and the resistor/thermo-sensor component. Altering the temperature we can regulate the evaporation of the odors. Also the obstacle recognition will be improved. We are currently working on a new dance model that is based on new sensor cameras with a bigger field of view and a faster processor that enables us to use the recognition even in the waggle run. We plan to recognize even the location and orientation of nearby follower bees to be able to adjust the robot's dance motion according to the followers' behaviour.

V. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of the German Research Foundation and reviewers' comments.

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