"SOZZY:" A Hormone-Driven Autonomous Vacuum Cleaner

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Abstract

Domestic robots are promising examples of the application of robotics to personal life. There have been many approaches in this field, but no successful results exist. The problem is that domestic environments are more difficult for robots than other environments, such as factory floors or office floors. Consequently, conventional approaches using a model of human intelligence to design robots have not been successful. In this paper, we report on a prototyped domestic vacuum-cleaning robot that is designed to be able to handle complex environments. The control software is composed of two layers, both of which are generally inspired by behaviors of living creatures. The first layer corresponds to a dynamically reconfigurable system of behaviors implemented in the subsumption architecture. The ability of the robot to support alternate configurations of its behaviors provides the robot with increased robustness. We have conveniently labeled particular configurations as specific "emotions" according to the interpretation of observers of the robot's behavior. The second layer simulates the hormone system. The hormone system is modeled using state variables, increased or decreased by stimuli from the environment. The hormone condition selects the robot's most suitable emotion, according to the changing environments. The robot hardware is built of off-the-shelf parts, such as an embedded CPU, inexpensive home-appliance sensors, and small motors. These parts keep the total building cost to a minimum. The robot also has a vacuum cleaning function to demonstrate its capability to perform useful tasks. We tested the robot in our laboratory, and successfully videotaped its robust behaviors. We also confirmed the hormone system to enhance the robot's plasticity and lifelike quality.

1. Introduction

Commercial cleaning robots are gaining some success in their field; for example [7]. They operate in commercial halls or other large spaces usually taken care of by commercial janitorial services. Their task is to navigate over horizontal surfaces, without colliding with obstacles on the floor, and to clean all open areas. In this case, the environment is quite predictable and unchanging, allowing the robot to build a convenient representation of the work space. Furthermore, the user of the robot is not an individual but a commercial enterprise, so a reasonable capital cost is acceptable, and the robot can be equipped with sophisticated mechanisms. Domestic environments are not as easy for robots to manage as commercial places.

In the 1980s, a variety of primitive home robots appeared on the market [3]. These robots had insufficient capability of sensing, moving, and computing, so the performance of the robots was disappointing. The popular approach taken by these robots is called the "sense-model-plan-action cycle." In this approach, a robot first senses the outer world; second, makes a CAD-type world model in its memory; third, makes an action plan according to the world model; and finally moves according to the action plan. This strategy is based on human intelligence, but in the real world, the robot's poor sensing capability cannot perceive the environment as precisely as a human does and the robot's actuators are far less efficient and dexterous compared to human hands and legs. In order to compensate for these poor capabilities, designers have tried to use more complex sensors and actuators, or to use more computationally expensive algorithms. As a result, these robots based on the human intelligence model tend to be expensive and big. However, the real world is still hard to handle for these robots.

In contrast to the previous approach, the subsumption architecture doesn't rely on the human intelligence model [1]. It is, rather, based on the intelligence of lower creatures, such as insects or animals. The subsumption architecture is composed of prioritized layers, each of which has an independent control and can handle the sensor inputs and the actuator outputs. Each layer or cluster of layers realizes a "behavior" of the robot. There are several merits to programming the robot in the subsumption architecture. First, the robot is robust in the real environment, because the robot's intelligence is distributed to each layer which runs in parallel. Second, intelligence can be incrementally programmed, starting from conditioned reflexes to a higher task-oriented behavior, allowing the robot to gain its ability step by step. Third, as the sensor information fed to the layers is quickly processed and is reflected on the actuator output, the robot's response speed to the environment is faster.

A weak point of the subsumption architecture is that each layer works independently without consideration of the total strategic plan. So the robot is sometimes trapped in a dead-lock situation, repeating the same reaction many times. In order to solve this problem, there should be a higher module over the subsumption architecture module to decide a long-term vision of what the robot should do.

As a result, to build an creature-type robot, we adopted the simulated hormone system as a higher module. The hormone system is simulated with several state variables that are influenced by stimuli from inside and outside of the robot. Each state variable also has a function to stabilize its own values [9]. The hormone system reflects long-term environmental changes on the subsumption architecture module by changing the priority between layers, and activating or deactivating layers. This makes the robot behave differently and adapt to the changing situation. Moreover, this mechanism gives the robot several characteristics which appear and disappear according to its hormonal condition.

According to a classic psychological study, observers who view a simple display of moving figures endow the figures with "human" qualities of intention and personality through perceiving their causal interrelationships and mutual relationships [5]. When the robot interacts with the world in several ways that change according to the situation, people will feel the robot has a "human" quality, such as a mood or an emotion. This can make the robot appear more friendly --- an important feature for a domestic robot. From this point of view, we utilize the hormone system not only to increase robot's flexibility but also to endow the robot with changing emotions according to the situation.

Our robot programmed in the subsumption architecture and the hormone system also has several merits in its physical appearance. As the control program does not require either a large computational power or sophisticated sensors and actuator, the robot can be small, light, quick, and cheap. The small robot navigates well in the domestic environment, as houses are usually built according to the size of a human. The light robot is also safe to its environment as any damage that it causes to a piece of furniture or a human in case it should fail is small, in proportion to its light mass. The small and quick robot does not occupy a great deal of space and can avoid a human quickly. On the other hand, a big and slow robot can be an obstacle to a person living there. Finally the robot made of off-the-shelf parts can be reasonably inexpensive, and, as a result, possible to purchase.

The prototyped robot based on the above mentioned concepts is named "SOZZY," and is round-shaped, ten inches in diameter, and includes all necessary parts in its body. The robot has many varieties of sensors, such as bump sensors, proximity sensors, a beacon detector, pyro human sensors, and a dust sensor. Its locomotion actuators are two geared-motor-driven wheels. It is also equipped with a vacuuming blower. The subsumption architecture module realizes the behaviors, such as obstacle avoidance behavior, human-interacting behavior, homing behavior, and foraging behavior. The hormone system controls the four emotions of the robot: joy, desperation, fatigue, sadness. Each emotion appears in the robot according to the situation.

The robot was tested in the real environment of the laboratory. The room was scattered with random objects, such as chairs, empty boxes, and garbage cans. First, the robot successfully demonstrated its robust navigation capability, starting from its home station, navigating around the room and returning to the home station. Second, the dynamic change of the hormone system was recorded in the real run of the robot. The change corresponds well with the robot's condition and situation, showing that the hormone system increases the robot's adaptivity. Finally, the robot demonstrated its real-task capability, the vacuum cleaning on the floor, which is programmed as a foraging behavior. The following sections present the hardware of SOZZY (Section 2), the subsumption architecture module and the hormone system (Section 3), and experimental results (Section 4).

2. Robot Hardware

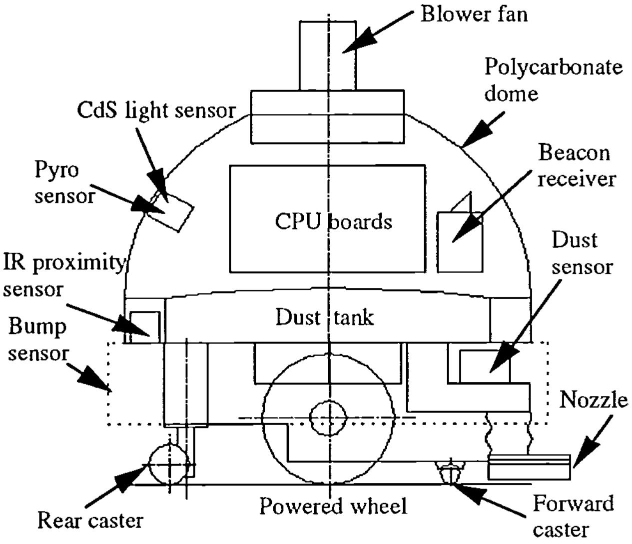


Figure 1. Schematic view of the cleaning robot SOZZY.

A schematic view of the robot is shown in Figure 1. General specification of the robot is shown in Table 1. The robot includes all necessary parts, such as CPU, actuators, sensors and energy source in its body. The upper half of the body is made of a polycarbonate plastic dome which consists of a vacuum chamber. The vacuum blower on top of the robot works as a vacuum source. Just in the middle of the robot is the dust filter which stops the dust in the dust chamber. From the point of view of maximizing the efficiency of the dust-vacuuming ability, microprocessors and other electronics are stored in the vacuum chamber. This design allows the dust filter to be wider and the vacuum loss to be minimal.

Total weight	7pounds
Width	10 inches in diameter
Height	11 inches
Maximum speed	2 feet per second
Locomotion	2 geared motor differential drives
Vacuum	30W DC motor blower
Workspace	Scattered bare floor
Battery duration	About 30 miniutes

Table 1. General Specifications for SOZZY.

The second design principle is to use off-the-shelf parts. This results in low building cost and short development period. The CPU boards we used are IS Robotics P1system which are based on 68HC11 (Motorola). These boards offer an environment to program the robot in a behavior based way and interface to off-the-shelf sensors. Vacuum cleaning usually requires a lot of power and is not so suitable for a small cleaning robot. But in order to avoid the excessive engineering challenge to develop a new cleaning mechanism, we used an off-the-shelf vacuum blower and a cleaning filter from Panasonic vacuum cleaners. A vacuum blower has a maximum power of 30W, but is usually used in much smaller power in the robot. Two 1500mAh NiCd batteries for radio control models are used for the robot, as IS Robotics' boards are designed for 7.2V NiCd battery packs.

Each of the sensors is relatively small, cheap and low-power. So the robot is equipped with as many sensors as possible. The sensors are listed in Table 2. In the future stage of the development, redundant or unuseful sensors can be omitted. Pyro sensors are sensitive to 8-10 micrometer wavelength infrared light, which is emitted from human body, and they can tell the presence of a human. The beacon receiver is shown in detail in Figure 2. This sensor utilizes an IR LED and several decoding ICs typically used in the tone decoders of touch-tone telephones. By the rotation of the mirror, the photodetector may scan around 360 degrees to find the maximum direction of the beacon signal. The direction of the mirror is also monitored by a potentiometer. This sensor gives the robot a minimum sense of the space its navigates, and enables the robot to return back to its home (i.e., the recharging station). The detail of the dust sensor is shown in Figure 3. To endow the robot with as acute a dust sensing ability as possible, this sensor utilizes the same techniques as a dust counter in a semiconducter manufacturing facility. The principle is that dust particles which pass through the laser diode beam shine instantaneously, and the shining is counted by the dust counter. This sensor also can adjust its sensitivity and detects a wide range of dust level from several thousandths of an inch sized dust particles to paper confetti which were often used in the experiments.

#	Sensor name	Function
2	Motor encoder	to measure wheel velocity
8	IR proximity sensor	to detect obstacles
8	Bump sensor	to detect collisions
4	Pyro sensor	to detect the presence of a human
2	Mechanical switch	to detect collisions of the nozzle
2	Motor current monitor	to detect motor stalling
2	Battery monitor	to detect battery level
1	Beacon receiver	to determine homing direction
1	Dust sensor	to detect dust particles

Table 2. Sensors used in SOZZY.

From both programming and construction standpoints, the differential drive can be the least complicated locomotion system [6]. The robot is aiming for insect-like robust and quick movement rather than accurate navigation capability. So this simple locomotion mechanism is employed.

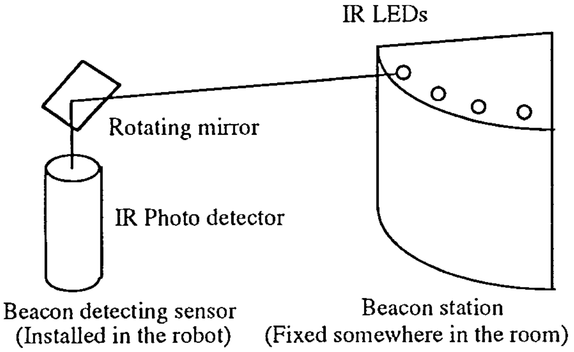


Figure 2. Beacon sensors to endow SOZZY with a homing capability

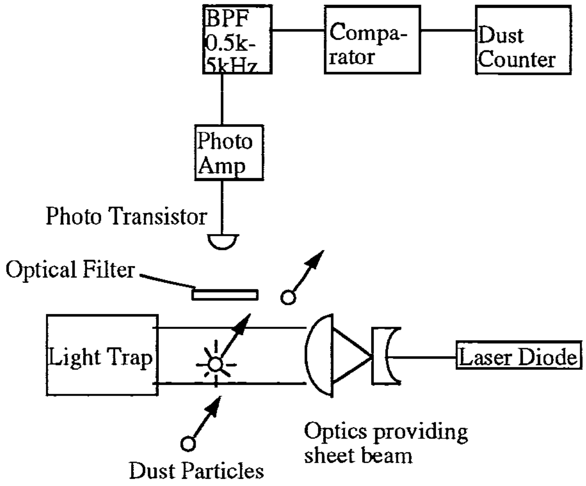


Figure 3. Acute dust sensing using a laser diode.

3. Software Architecture

Each behavior is programmed in the Behavior Language [2]. For example, SOZZY's cleaning behavior is programmed as follows. SOZZY has a dust sensor with which it can tell that it has "eaten its bait." So the cleaning behavior is programmed as a foraging behavior to try to follow the dust distribution to eat more. After trial and error, we have found that a swinging motion to the left and right seems to be most effective for the robot. Figure 4 shows how the foraging behavior is programmed in the combination of AFSMs (Augmented Finite State Machines). The oscillator AFSM generates timing for the swing AFSM to control the basic wheel movements. The dust detect AFSM sends messages when the dust count exceeds a certain level. These messages first stop forward movement to stay there for a longer period, and then, second, reset the oscillator AFSM so that the robot swinging center should be the current location where dust is found, and then, third, trigger the monostable to lower its sensitivity resulting in ignoring small dust density for a certain period. The dust counter also triggers vacuuming AFSM to make vacuuming stronger.

In the subsumption architecture, several layered behaviors compete over control of the robot. As each behavior has direct connection to sensors and actuators, a tight connection of sensors and actuators are realized. This results in quick response of the robot and robust behavior. This layered structure also facilitates programming and debugging. Each behavior can be programmed and debugged separately, as most of them can operate independently. As a result, programming and debugging can be progressive and incremental. On the other hand, the weak point of the subsumption architecture is its fixed combination and prioritization of behaviors. This often results in a lack of flexibility or local minimum problems.

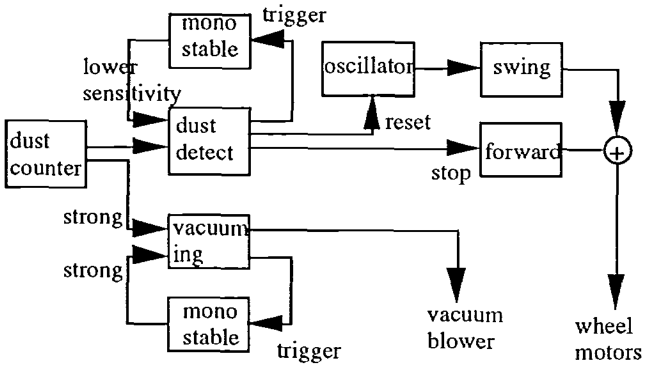


Figure 4. Foraging behavior (Vacuum cleaning behavior).

In the process of programming the robots, we prepared several versions of the program which have a different combination and prioritization of behaviors. Basically each version has the same repertoire of behaviors, but the connections between behaviors and actuators are different. This difference of connections between behaviors gives the robot a different tendency of interaction to the environment. From the point of view of programming the robot in a creature-like way, we call each combination of behaviors as an emotion of the robot.

In order for the robot to have several emotions, which appear and disappear according to the situation, an emotion switching mechanism is implemented. The emotion switching mechanism is realized in behavior language as shown in Figure 5. The connections of each behavior are prewired and form a network of connection wires. Their connection to actuators are usually inhibited by emotion suppressing behavior. Once some inputs are given to emotion enabling input nodes A or B, this inhibition is removed and the emotion appears on the robot, as shown in Figure 6. When messages are sent to node A, behaviors X and Z can control the actuators with higher priority of Z over X. On the other hand, when messages are sent to node B, behaviors Y and Z can control the actuators with higher priority of Z over Y. There are several good points of this mechanism. First, it doesn't increase the amount of computation, as it only adds a network of inhibition and suppression connection wires. Second, debugging each emotion is easy, as each emotion is completely independent and can be tested separately. Using a macro function of the Behavior Language, the network of the connection wires can be generated automatically.

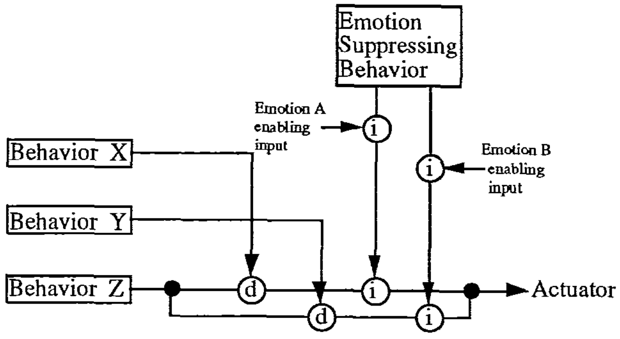
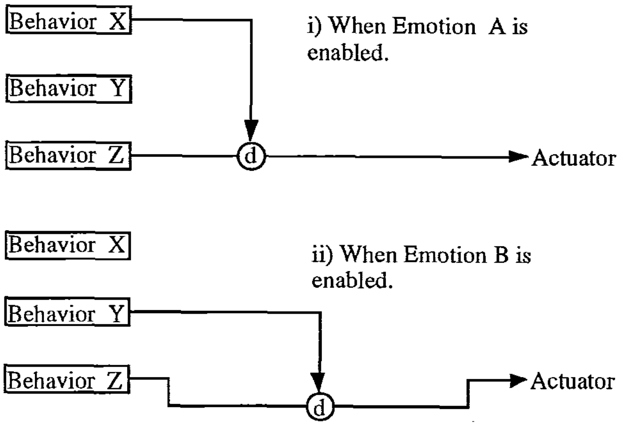


Figure 5. Emotion switching mechanism using connection wire network.



i) When Emotion A is enabled.

ii) When Emotion B is enabled.

Figure 6. One emotion is selected by messages sent to the emotion enabling input.

The code example of "joy" emotion is listed in List 1. The keyword :motor-behaviors introduces the priority and combination of motion related behaviors. In this case, the highest priority is the escape-stall behavior which prevents motors from overheating by stalling. The keyword :blower-behaviors introduces the priority and combination of vacuuming related behaviors. The keyword :connections introduces the connection wires which should be enabled only when this emotion is active. These wires are used to connect a behavior to a virtual sensor behavior. The virtual sensor behavior is responsible for processing sensory data into more understandable data [4]. By changing the virtual sensor behaviors connected, the behavior can effectively change its reaction without modifying its own function. As a result, in "joy" emotion, the robot concentrates in eating a bait and exploring to other places as long as it can find a beacon signal. Once it loses the beacon signal, it tries to go back as soon as possible along the way it has come. Based on this "joy" emotion, other three emotions are programmed in slightly different ways. In "desperation" emotion, the robot behaves a little roughly without using the obstacle avoidance. In "fatigue" emotion, the robot tries to go home as fast as possible without trying to do anything else. In "Sadness" emotion, the robot gives up further navigation and vacuuming, and when it detects a human, it asks for help by edging up to the person.

```
(defemotion Joy
  :motor-behaviors
     (explore
      sweep
      homing
      avoid
      dead-reckoning
      bump
      escape-stall)
  :blower-behaviors
     (suck-weak
      suck-strong)
  :connections
     ((connect (beacon-recover pb1)
               (dead-reckoning pb))
      (connect (beacon-recover go-dir1)
               (homing go-dir))))
```

List 1. Code example of "joy" emotion.

In order to appropriately switch the emotion of the robot, there should be a higher module over the emotion switching mechanism and behaviors. From the analogy of living things, the emotion should be controlled by some internal state, such as hormones. Action selection using hormone-like state variables have been researched[8]. The emergent behaviors by controlled quantity with disturbers and stabilizer are examined[9]. In both cases, the appropriate behavior is selected according to the condition of its internal state variables. These processes are distributed over behaviors and are robust and dynamic.

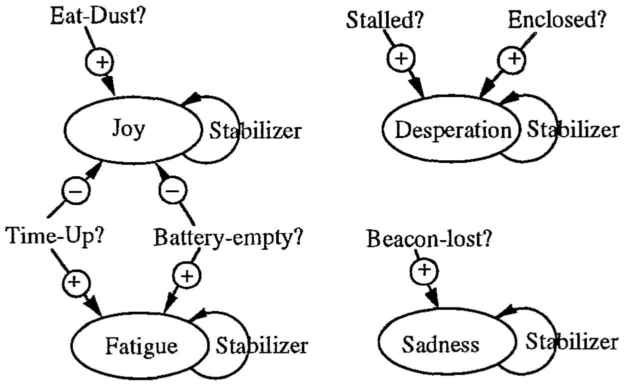


Figure 7. Simulated hormone system corresponding the four emotions.

In our robot, we utilized this technique for selectively activating one of four emotions. Figure 7 shows the hormones corresponding to the four emotions: joy, desperation, fatigue, and sadness. All hormone values have a disturber, such as "Eat-Dust?." If these condition are satisfied, the hormone value increases or decreases slowly. When the robot vacuums the dust, "joy" hormone increases (Eat-dust? disturber). When the battery or preprogrammed operation time is expiring, "joy" hormone decreases and "fatigue" hormone increases (Time-up? and Battery-empty? disturbers). When the robot stalls or it detects too many obstacles around it, "desperation" hormone increases (Stalled? and Enclosed? disturbers). Finally, "sadness" hormone is increased, when the robot loses the beacon signal (Beacon-lost? disturber). Among these four hormones, the greatest hormone value realizes its emotion on the robot. There are also stabilizers to try to keep the hormone value to an initial level and avoid saturation. This mechanism prevents any hormone from always being dominant in certain circumstances resulting in the loss of robot flexibility. The hormone system usually changes relatively slowly on the order of several seconds or several tens of seconds, getting influence from external or internal conditions. As a result, the emotion switching doesn't happen frequently. So a lower module takes care of fast response and the hormone system tries to increase the robot's ability to change itself according to the situation.

4. Experimental Results

SOZZY's navigation capability was tested in a real laboratory environment and videotaped.

In each experiment, the robot is programmed in advance to return to its home (the beacon station) after five minutes. Figures 8 to 11 show how the robot behaved in the laboratory. The movement of the robot was recorded manually using videotape. The reason why the robot can go back to the beacon station is that it is programmed not to go out of the view of the beacon station. Even when the robot happens to lose the beacon signal, it tries to backup its way to the point where it can find the signal.

The hormone condition of the robot was also recorded in the real run, as shown in Figure 12. In order to record the conditions of the quickly moving robot, we used a radio modem. To obtain a space for the radio modem, we had to remove the vacuum blower and disable the vacuum cleaning ability. As a result, joy-hormone doesn't change by dust detection. In the figure, during the first 40 seconds, joy-hormone is dominant. And in the next 20 seconds, as we intentionally shadow the beacon station from the robot, sadness-hormone increases. From around 90 seconds, desperation-hormone becomes dominant, as the robot headed into a messy area of cables and small equipment. After 120 seconds, as it tries to go back to the beacon station, fatigue-hormone gets high and joy-hormone gets low. The fatigue-hormone and joy-hormone are oscillating in this period because the stabilizers are trying to prevent saturation and are resetting the hormone values to their initial levels. Usually, a stabilizer gradually forces an unsaturated hormone to converge to its original level, as seen in the sadness-hormone graph after 60 seconds.

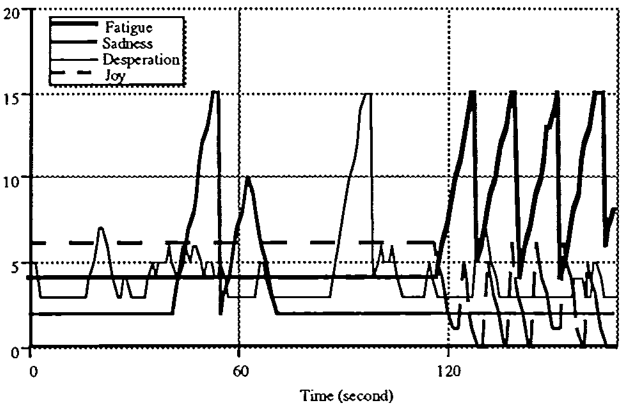


Figure 12. Hormone variation in the real run of SOZZY.

As a by-product of hormone-driven emotion switching, the robot seems to be more friendly and more lively. For example, during the experiments, we tried to enclose SOZZY with pieces of wood. First, the robot wandered around, but finally it began to try to push a piece of wood (like a small child to get angry). Next, we moved a piece of furniture and intentionally obstructed the robot's view to the beacon station. First, the robot tried to back up by itself to the point where it could see the beacon again. But finally knowing that it could not find the beacon signal any more, it changed its attitude to approach to a human for help (in sadness emotion).

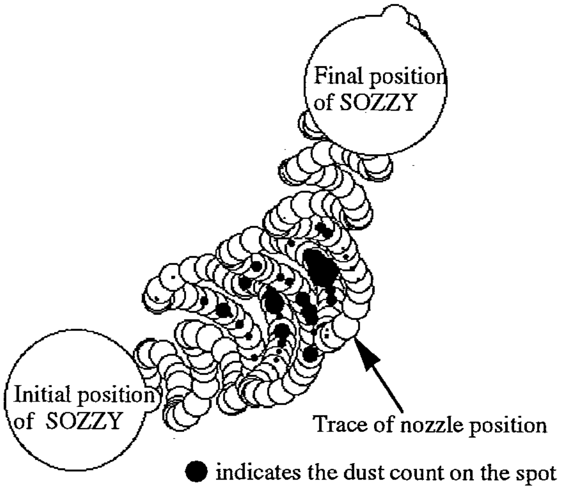


Figure 13. Dust following using the dust sensor.

To experiment with dust is not easy, as dust distribution in every experiment is different. In order to facilitate the experiment, we have used paper confetti as simulated dust. Figure 13 shows how the robot behaves in an island shaped dust distribution. The experiment was done on the real robot, and the data of dust count, right wheel velocity, and left wheel velocity are retrieved by a tether and shown onto the computer display. White circles indicate the nozzle position of the robot, and black dots show the dust count on the spot. This figure shows well how the robot follows the dust distribution by a swinging motion. Once the dust is vacuumed, the distribution of dust changes. This makes it difficult for the robot to follow the dust distribution perfectly. But together with the robust navigation ability, SOZZY should be able to eat up dust.

Programs written in the behavior language are compact and require minimal calculation. At this stage, SOZZY's behavior program occupies 17kbytes of memory, and still requires only 5% of the calculation power of the

68HC11 CPU running at 8MHz. The prototype also contains two slave CPUs for motor servo control and sensor processing. This configuration of three CPUs makes program development easy. Judging from the compactness of the behavior program, it seems possible to control all of SOZZY's function with one 68HC11 CPU.

There are several points to improve on the robot. First, the wheeling motor's power turned out to be weak compared to the total weight of the robot. This makes a delay of motion in response to a command. Such a delay in the robot makes programming troublesome. In order to guarantee the quick movement of the robot, the ratio of the motor power and the robot's weight should be improved. The vacuuming mechanism, which includes the vacuum blower, vacuum chamber, dust chamber and nozzle, seems to be inefficient. A lot of improvement will be required in this field. Sensor configurations should also be optimized. In SOZZY's case, as it uses totally off-the-shelf parts, there was a limitation in the sensor configuration. From our experience, bump sensors seem to be most important sensor in the unstructured environment. So in order to maximize its capability, we think the robot should be as light as possible (because a light robot won't give damage to others even if it bumps), and the bump sensor should cover all the surface of the robot (as the bump to a piece of furniture can happen at any height)

5. Conclusion

A prototype of a hormone-driven autonomous domestic robot has been developed. This robot is programmed in a behavior based manner, and can behave quickly and robustly in an unstructured environment. This robot has four different configurations of behaviors, which we call four emotions of the robot, as each of them makes the robot behave in a characteristic way. The robot also has a simulated hormone system which controls emotion switching. This emotion switching driven by the hormone system not only successfully increases the flexibility of the robot without increasing CPU computation, but also makes the robot more friendly and more lively. Although from the point of view of efficiency or accuracy, the robot still cannot execute a perfect job at this stage, these elements of the robot should add some value to its existence. Using the features, such as robustness, quickness, and friendliness, we would like to realize a small, affordable, and enjoyable domestic robot in the future.

6. Acknowledgments

I would like to express my great thanks to Prof. Rod Brooks, who allowed me to build SOZZY, IS Robotics Co., who not only supplied the robot's electronics, but also offered technical assistance, the members of Mobot lab, and Michael Caine, Erik Vaaler and Ron Wiken, who helped me a lot in building the robot. I also thank my colleagues in Matsushita Research Institute Tokyo, Inc. who named the robot SOZZY as a combination of "Soji" (means cleaning in Japanese) and "Fuzzy" (Fuzzy control is a popular keyword in Japanese home appliances) ,wishing the robot also to be popular. And finally I would like to express my thanks to Gary Borchardt and Lynne Parker for smart suggestions and reviews of my English.

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Figure 8. SOZZY's navigation in a laboratory environment (1).

Figure 9. SOZZY's navigation in a laboratory environment (2).

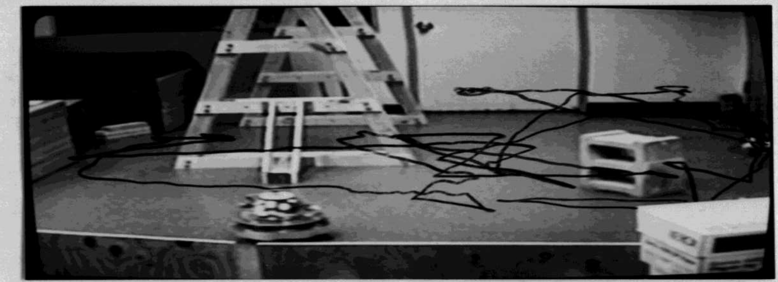

Figure 10. SOZZY's navigation in a laboratory environment (3).

Figure 11. SOZZY's navigation in a laboratory environment (4).

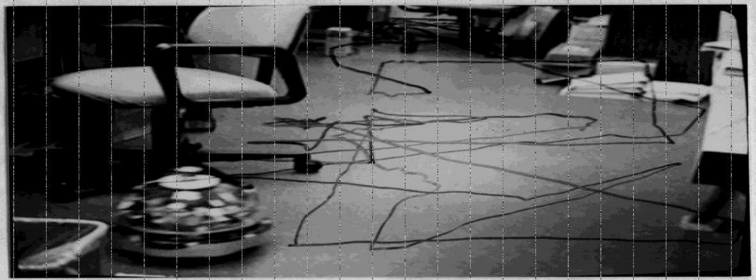

Figure 8. SOZZY's navigation in a laboratory environment (1).

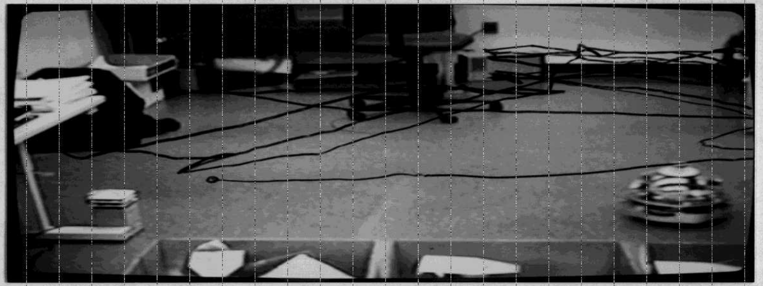

Figure 9. SOZZY's navigation in a laboratory environment (2).

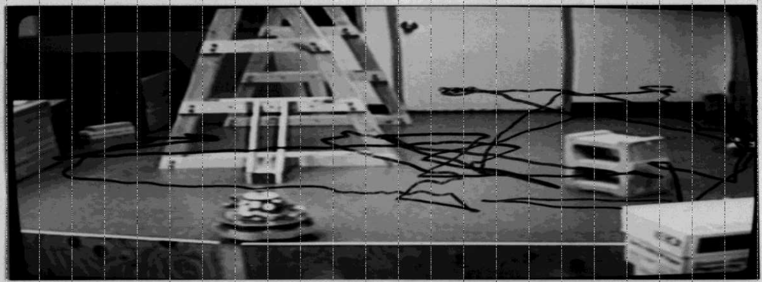

Figure 10. SOZZY's navigation in a laboratory environment (3).

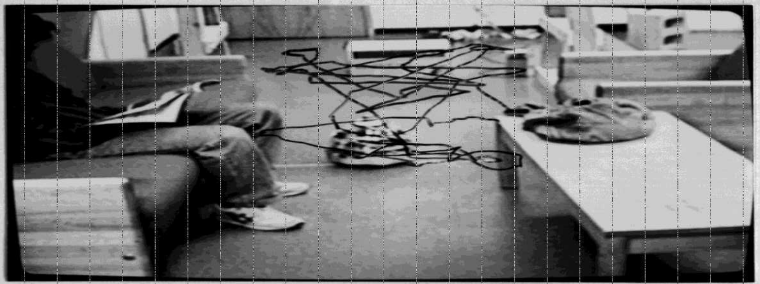

Figure 11. SOZZY's navigation in a laboratory environment (4).