Fascination of Down Scaling – Alice the Sugar Cube Robot

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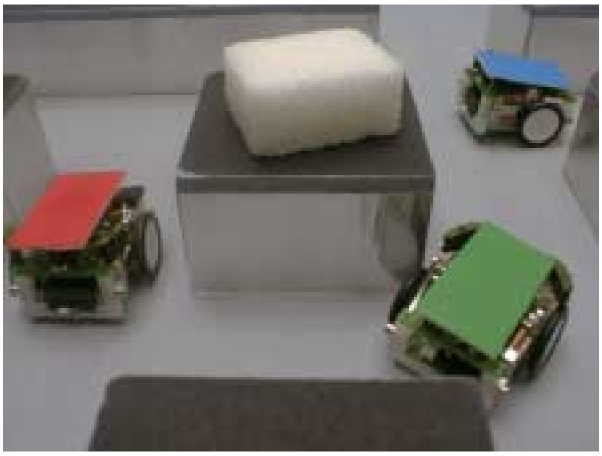

Figure 1: 3 mobile micro-robots Alice in a labyrinth. The robots and the sugar cube have the same size!

Abstract:

Design of mobile micro-robot (MMR) is still a challenge due to the restricted availability of basic components. However, the number of highly integrated microelectronic and micro-mechanical components is growing fast. Nevertheless, its integration to a micro-system requires a good knowledge of all the interactions between sensor, actuator, computation and energy source. Often compromises between performance and power consumption have to be found.

This paper gives the basic considerations for building mobile micro-robots. The major scaling effects are presented and their impact on micro-system design is discussed. The mobile micro-robot Alice (fig. 1), having the size of a sugar cube, is presented and discussed in the context of scaling laws. It has an autonomy of around 10 hours and is able to navigate based on simple behaviors like obstacle avoidance or wall following.

Keywords: robot scaling, mobile robot, micro-robot.

1 Introduction

With the progress in micro- and nano-technologies (MNT), a large number of sensors and actuators operating in the sub-millimeter range have appeared. Subsequently, various research groups started recently to develop micro-robotic systems for a wide range of application: precision tooling, endoscopic surgery, biological cells manipulation, AFM microscopy, etc. However, these devices are not really autonomous, neither concerning energy supply nor intelligence. But autonomy is a major issue for a lot of innovative application of micro-robots where teleoperation is not possible or not desirable. Typical examples might be found in medicine, where micro-robots could deliver a medicament exactly were needed or in inspection and exploration, where a much larger surface can be covered when using a large quantity of micro-robots [Garcia97]. To advance towards such very challenging applications, it is of high importance to identify the key parameters that limit downscaling [Nicoud95], [Shimoyama95]. Mechanical miniaturization has already been investigated several decades ago [Burckhardt72]. As most of the envisioned micro-robots are still in the domain of classical physics, the classical theory is still applicable to establish the basic scaling properties of the domains in question. Scaling laws express the dependence to a scale effect for physical parameters and are usually expressed in function of a reference length L. Two procedures are possible: applying an isotropic modification of the dimensions or holding some parameters invariant with respect to the scale and study their influence on the other parameters. The aim of this article is to discuss and analyze the scaling laws and to verify some aspects on an existing mobile micro-robot.

This paper is organized in two major sections. The first section highlights different scaling aspects for MMR, trying to be as general as possible. In the second section the micro-robot Alice is presented and discussed as a case study.

Within our current research activities we concentrate on robots sizing between a couple of millimeter up to a couple of centimeters. Throughout the text, we will use L as the characteristic length of reference.

2 Laws of Scaling

Within this section we will discuss the most important scaling effects related to mobile micro-robots. Of course the scaling law approach has some limitations because just gives the tendency of a physical dimension when scaling down. Real and practical values (e.g. force of actuators, energy of a battery) depend essentially on technological aspects. The discussion is not exhaustive, however it should give a basic understanding of the scaling effects and its consequences on the design of mobile micro-robots.

2.1 Mechanics

The first where the similarity laws can be applied is the mechanics of the robot. Mechanical properties are well understood and scaling effects have been investigated and verified for several decades [Drexler92].

The dimensions related to the volume (mass, inertia) are proportional to L^3, whereas dimensions related to the area (cross section) scale down only with the exponent 2.

Moreover the structural stiffness and the stress related to the mass scale linearly with L. This is a great advantage for smaller systems which are intrinsically more robust against destruction forces related to their own mass. In the design we can thus choose thinner and less bulky structures or weaker materials still conserving a good rigidity. An evident example is found in nature if one compares the cross section of the leg of an elephant with that of an ant. Additionally the structural eigenfrequencies increase linearly with $1/L$, thus we can expect less interference with structural resonances.

Surface friction depends on the normal force, which is proportional to the mass (L^3). But the energy E_μ lost by friction scales down more importantly assuming relative displacements proportional to L. This is true for small motors or gears, where one can use slider bearing instead roller bearings. However, it holds only if we assume to keep the rotational speed constant, which is not the case for many components.

Unit	Scaling	Comments
Volume, Mass:	$Q \sim L^3\ ;\ m \sim L^3$	
Mass related force:	$F \sim m \sim L^3$	acceleration, gravity, impact forces
Friction forces:	$F_\mu = \mu \cdot F \sim L^3$	e.g. contact between wheel and surface
Energy losses due to friction:	$E_\mu = L \cdot F_\mu \sim L^4$	assuming that displacement scales with *L*
Potential energy:	$E_p \sim h \cdot m \sim L \cdot L^3 = L^4$	
Wind, lift, drag forces:	$F_w \sim L^2$	
Stiffness	$c \sim L$ $c \sim \frac{b \cdot h^3}{l^3} \sim L$	of a beam
Stress:	$\sigma \sim \frac{F}{L^2}$	beam exposed to an external force *F*
	$\sigma_{\max} \sim \frac{F \cdot l}{b \cdot h^2} \sim \frac{L^3 \cdot l}{b \cdot h^2} \sim L$	beam expose to its own mass
Structural eigen-frequencies:	$f_0 \sim \frac{1}{L}$ $f_0 = \sqrt{\frac{c}{m}} \sim \sqrt{\frac{L}{L^3}} \sim \frac{1}{L}$	elastic beam

Table 1: scaling of some mechanic quantities.

Air drag and lift depend on the area and thus are proportional to L^2. This can be an advantage but also a disadvantage in some cases. Due to this effect, a flying robot might fly much slower, thus simplifying the control. However, secondary fluid effect might play a dominant role for small systems. A falling miniature robot has much better chance to survive because of the increasing ratio between air drag and mass. This effect is additionally supported by the mechanical properties mentioned above. On the other hand a small land robot is much more exposed to wind and friction with the terrain could be insufficient for staying stationary (friction $\sim L^3$, drag $\sim L^2$). These air drag effects become also very evident in nature. A small animal, e.g. an ant, can easily survive a fall from a multi floor building, whereas an elephant will be seriously hurt when falling from around 1 meter.

2.2 Scaling effects on mobility

The size of a mobile robot has strong implications on the mobility in a given environment. Wilcox [Wilcox97] introduced the "*mean free path*" as the average distance a robot can move before it encounters a non-traversable obstacle. This distance depends on the size of the robot, the maximal surmountable obstacle height and the terrain morphology (rock distribution and size). For a given terrain there is a range of optimal dimensions. However, it should be noticed that small robots can surmount higher obstacles in relation to its size. This is due to the fact that the required energy to get on an obstacle of its own height is proportional to L^4 ($E_{pot} \sim h \cdot m \sim L \cdot L^3$) and thus decrease faster then the mass (volume). Evident examples from the biology are again small insects against big animals. Insects climb relatively high obstacles in their daily live. Some of them e.g. fleas or grasshoppers even prefer jumping. They jump over 20 cm, which is many times their height whereas kangaroos jump up to a couple of times their height.

Another aspect of mobility is the speed of movement. Observations in nature and of autonomous mobile robots show that the speed scales approximately linear with L. There are of course large variations in velocity between different species/robots of the same mass, but in average the linear scaling law holds. As we will see later, this is related to power, energy, control and also sensors of MMR.

2.3 Actuators

Actuators are one of the major problems in designing miniature robots. The main reason is the lack of commercially available micromotors and the low performance of the existing ones. For a good overview on electrostatic and electromagnetic actuators please refer to [Dario92] and [Fearing98].

Most actuators such as combustion engines, pneumatic, electromagnetic, electrostatic, ultrasonic, shape memory alloy, piezoelectric or biological muscle used for large systems might also be useable in micro-robots. However, some of them might be very difficult to build in small size and thus are useless for our investigation. Others are very interesting and promising but not yet well developed and present important drawbacks (low speed, high voltage, low forces, …). One of the most promising and interesting solutions in long term might be artificial muscles that show excellent scalability in nature. However, they are still far from real applications.

One of the actuators that are already available in small scale are electromagnetic motors. For scaling of electromagnetic motors we can find for the torque M [Jufer95]:

- $M \sim L^5$, assumption constant efficiency
- $M \sim L^{3.5}$, assuming similar motor temperatures.

In reality the scaling might lay somewhere in-between the two assumption above. Although this scaling effect of the motor torque is somewhat unfavorable, electrical motors still represent one of the most interesting solutions because of their availability (see table 2) and ease of control.

Motor Type	**torque** [mNm]	**power** [mW]	**speed** [rpm]	**volume** [mm^3]	**eff.** [%]
Smoovy 3 gear 1:125	2.0	12	120	110	6
Minimotor 1.9 mm gear 1:47	0.15	3	425	27	8.25
Wobble from SSSA	0.35	2.6	185	195	4.7
ETA lavet by Swatch	0.35	1.3	60	210	6.3

Table 2: Examples of small motors (tested in a limited temperature range).

For an autonomous robot a motor with a good energetic efficiency should be preferred, but as torque scales with L^5, the mechanical power quickly becomes smaller for decreasing L. In practice the volume of the coil become predominant over the magnet, increasing significantly the overall size. On the contrary, the motor designers are mainly interested in a good power to mass ratio, and normally prefer a much lower efficiency and a higher working temperature. This is allowed because the surface to volume ratio ($L^2/L^3 = L^{-1}$) responsible for heat dissipation is scaling favorably.

Assuming constant surface speed on the rotor, the rotational speed Ω of a motor scales with $1/L$. Thus small motors require gearboxes with high reduction rates which additionally reduce the efficiency.

2.4 Energy source

Mobile micro-robots (MMR) require an on-board energy source or the capability to generate energy from an external source. The most obvious energy sources are batteries, accumulators, supercaps, springs, fuel or solar cells. The scaling properties and power density of the different energy sources are presented in table 3.

Among the electrical energy storages, batteries have the highest power density and an excellent availability in many different sizes. Accumulators and supercaps have lower energy density but are rechargeable, thus also compatible with power generators (e.g. solar cells). The energy density of supercaps is very limited, but, compared to accumulators, they allow much higher currents for charging and discharging.

Fuel has a very high energy density, but it might be a great challenge to build small size combustion engines and generators. The technology is not available today.

Finally, solar panels become interesting in small size because of their advantageous downscaling effect. However, in most cases they have to be combined with accumulators or supercaps.

Energy Source	**scaling**	**energy** [Wh/l]	**energy** **[**Wh/Kg]
Battery	L^3	230 - 1300	51 - 408
Accu	L^3	40 - 210	11 - 61
Supercap	$\sim L^4$	1.8 (@ 9 cm^3)	1.6 (@ 9 cm^3)
Spring	L^3	0.07	
Fuel	L^3	13000	13000
Solar panel	L^2	0 - 100 W/m^2	

Table 3: Energy sources.

The scaling properties given in table 3 are derived form real examples and some simplified models not considering the housing. Consequently the given values might be somewhat optimistic. However, taking into account current technology and availability, the most promising power sources for MMR are still batteries or the combination of solar cells and accumulators.

2.5 Sensors

As we are interested in autonomous mobile robots, sensors for environment perception are of high importance (table 4). In relation with scaling, the power consumption of sensors might become the major issue. Generally, we can distinguish between passive and active sensors. Passive sensors do not irradiate energy in to the environment (e.g. camera, microphone) whereas active sensors send out some sort of signals that support the measurement.

In consequence, the power consumption of passive sensors is dominated by the signal conversion and processing, which is barely changing with the robot size. In contrast, active distance sensors like sonar, IR proximity sensors, triangulation (Position Sensitive Device), light stripe, laser range finder, magnetic or radar emit energy and use the reflected beams dispersed by the object to measure. We might assume that the required measurement distance is proportional to the characteristic length L, which makes sense if the robot speed scales linearly. Under this assumption, the emission power depends on L^2 (surface of the sphere where the reflection is dispersed) multiplied by an exponential factor function of L (e^{kL} representing the energy dissipation). However, even if $L^2 \cdot e^{kL}$ is favorable for small size, active sensors might have power a consumption that is not feasible for MMR. Thus passive sensors or very simple active sensors are the right choice for small systems.

sensor	**principle**	**output**	**comment**
Bumpers	contact	on-off	easy
Compass	magnetic	angle	feasible
Inclinometer	inertia	angle	feasible
Barometer	pressure	bar	feasible
Temperature	heat	^{o}C	easy
Microphone	sound	Hz	feasible
Photodiode	light	LUX	feasible
Camera	light, position & color	value per pixel	not easy and much information
Sonar	time of flight	proximity	not for short range
Infrared	reflected light	proximity	feasible
PSD	reflected angle	distance	to be integrated
Laser ranging	time of flight	distance	difficult

Table 4: Possible sensors for MMR.

2.6 Control, Processing

The controller of a robot has to process information and generate adequate actions. This task might not change much with the size of the robot. However, we might argue, that smaller system have a more restricted, thus less complex environment to deal with. This might allow a group of small robots to fulfill a task with lower computational power per robot. Additionally, small robots are moving slower, thus requiring less demanding sampling times for reaction. However, these effects will in most cases not compensate for the important reduction of calculation power with size.

As we have seen above, the available energy of a MMR scales with L^3. The required power P_{CPU} of a microprocessor is related to the number of transistors n, the clock frequency f and the power supply V_{dd}.

$$P_{CPU} \sim n \cdot f \cdot V_{dd}^{\,2}$$

If we assume $f \sim velocity \sim L$, the power consumption scales linear with L. However, because the available power is scaling with L^3, we still have to admit a reduction in calculation power by L^2, thus drastically limiting control capacity. It is therefore a must and not a choice to further reduce the calculation power by using 8-bit instead of 16 or 32-bit microcontrollers.

In consequence, we have to admit that the intelligence of MMR will be limited. Nevertheless, in connection with an external supervisor (computer, human) or an adequate collective approach, small robots might still be able to fulfill complex tasks.

2.7 Communication

Communication in MMR takes place between different units or between the robot and the supervisor or user. The communication can be unidirectional or bidirectional, involving a receiver, a transmitter or both on the robot.

The power consumption and the dimension of communication devices often depend less on the communication distance but more on the precision, the conversion technique and the communication speed.

Receivers have relatively low power consumption but as they are almost always operating, it becomes an important power drain for MMRs.

Transmitters irradiate power like an active sensor. Thus the power consumption depends on $L^2 \cdot e^{kL}$, where L is the communication distance that we assume again proportional to the size of the MMR.

Communication can be established through infrared, visual signaling, sound or radio. For short range, infrared becomes interesting because of the favorable $L^2 \cdot e^{kL}$ scaling and it is much simpler than radio. Moreover, clever combinations of different concepts for the sender and the receiver might reduce power consumption. For example the robot could receive infrared signals and answer with a particular movement or it could use its IR distance sensor also for communication. In any case, communication is quite power consuming for a MMR and thus should be reduced to a minimum. This favors solutions where the robot operates autonomously using its on-board capabilities only.

3. The mobile micro-robot Alice

The mobile micro-robot Alice (fig. 2) is presented here as a case study to demonstrate and verify the scaling law discussed above. It is an excellent example of a miniaturized and highly integrated mechatronic product. Other research laboratories around the world have also developed similar MMR, among them:

- Artificial Intelligence Lab at MIT [McLurkin96]
- Microprocessor and Interface Lab at EPFL [LAMI]
- Department of Micro System Engineering at Nagoya University [Fukuda99]
- Institute for Complex Engineered Systems at CMU [Navarro99]
- Sandia National Laboratories in Albuquerque NM [Sandia01]

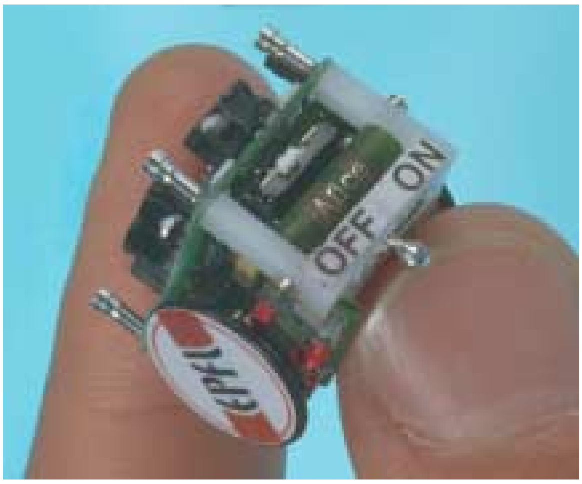

Figure 2: The newest version of the mobile micro-robot Alice with its motor and sensor module assembled into the plastic chassis.

Alice is one of the smallest intelligent mobile robots in the world (table 5-7). The remarkable long power autonomy of about 10 hours makes it very particular and unique in its class. Simplicity, modularity, hardware and software flexibility, robustness and affordable price are further advantages. Maybe these features and the accumulated experience were decisive for the victory at the Micro Maze Contest (editions ‘98 and ‘99) in Nagoya, Japan.

In agreement with the conclusions drawn from the section on mechanical scaling, Alice can fall down from 1 meter without serious damage and can fall down twice its own height without any problem (~5cm).

Dimensions	21 x 21 x 12 mm
Weight	5 g.
Velocity	40 mm/s
Power consumption	4 mW - 10 mW
System autonomy	up to 10 hours
Infrared remote communication	6 m, 500 bps
Infrared local communication	4 cm, 500 bps
Radio communication	10 m, 1000 bps

Table 5: General characteristic of Alice.

In contrast to big robots, the supporting structure is made of plastic and printed circuit board. The material cost is only of about $ 50, whereas the assembling time for the prototypes is still approximately 3 hours. An automated assembly is feasible for high quantity production.

Table 5 gives the main characteristics of the robot. Alice reaches a maximum velocity of 40 mm/s (twice the length) that demonstrates the scaling linear with *L*. Bigger robots of about 1 cubic meter run about at 1-3 m/s.

The power consumption of the motors of 3 mW is about 30% of the total power consumption and thus still very important part (table 7). Moreover it should be noticed that the motors, being probably the most critical component, mainly give the size of Alice.

Mechanical structure	plastic frame and PCB
Motors	2 Swatch motors
Motion	2 wheels on the minute axis
Energy source	3 button batteries (1.5V, 23mAh) + voltage regulator
CPU	PIC16F84 @ 4 MHz
Sensors	4 infrared proximity sensors
Communication 1	Local with the same 4 proximity sensors
Communication 2	One way IR with dedicated circuit (1 diode + 2 OpAmps)
Communication 3	One way IR with RC5 standard
Communication 4	Both ways radio. On-off keying

Table 6: principal parts of Alice.

As argued in section 2.4, also for Alice, chemical batteries are the best power source. Because of the limited power of these button batteries, a voltage regulator was used to ensure a stable supply voltage.

Active proximity sensors are used for environment perception. They are very simple to use and have a limited range of 2 to 3 cm (similar to *L*). To minimize power consumption, measurements are taken only every 50 ms. This is still enough for reliable obstacle avoidance at Alice’s top speed. In this particular case we see again how energy, sensors, control and mobility are closely connected and a compromise was found.

unit	average [mW]	peak [mW]
motors (1x)	1.5	2.5
CPU	3	
sensors	0.5	18
infrared rx	0.6	1
local communication		18
radio rx	3	3
radio tx		30
The robot	~ 10	~ 45

Table 7: power consumption of each subsystem.

Another main power drain is the microprocessor, also using 30% of the total power. The program is written in Assembler, allowing optimizing the code and reducing memory space to a minimum. Behaviors like obstacle avoidance or wall following are implemented on the microcontroller.

Finally different ways of communications are available:

- unidirectional IR communication for teleoperation based on the behaviors like obstacle avoidance or wall following
- bidirectional IR communication with distance sensors for robot to robot short range communication

- bidirectional radio communication used for communication with an external supervisor. This allows for automatic map building in simple labyrinths

3.1 Applications of Alice

The robot Alice is already used in various research and educational projects [Caprari00]:

- localization and map building
- local and global planning methods with hybrid (metric-topological) environment models
- semi-autonomous operation via Internet [Siegwart98] or Matlab
- robot soccer
- research platform for biologists
- ludic applications

Furthermore, Alice is an inspiration for other mobile robots and autonomous systems in general. For the first prototype of a micro-robot for space exploration (fig. 3) we basically connected 2 Alice, attached bigger wheels and used the same IR receiver module to perform the first experiments [Freese99]. The result was a fascinating robot for rough terrain with on-board inspection camera and autonomy of over one day.

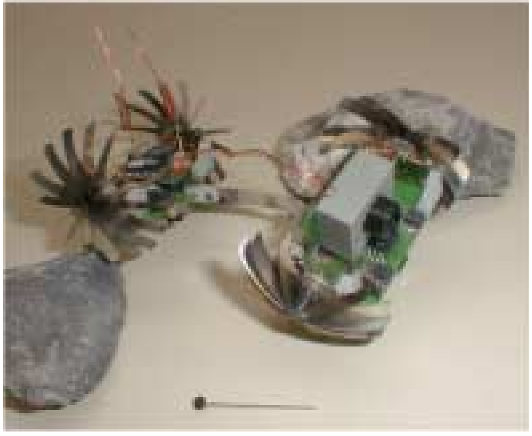

Figure 3: LAMAlice: The off-road sister of Alice. It is composed by a front and rear module connected with a flexible metal blade. The four actuated wheels are also made of radial blades.

The reduced size of Alice, together with the long power autonomy make it a privileged candidate for investigations and experiments in collective robotics. For this kind of research the main interest is the collective behavior of a group of interacting units and the algorithms governing them. The key elements are local communication among teammates, reaction to the environment sensed locally and stochastic decisions. Many concepts for the design of such robot control are derived from the biology and the ethology, manly from the study of social insects like the ants [Bonabeau99]. The robots serve also to confirm those theories by mean of experiments with robots programmed to act as modeled insects. Further proceeding in this direction and given that the size of MMR is reaching the size of real insect (fig. 4), a new opportunity is open. It is now possible to let interact living creatures and robots in a mixed society and thus to analyze and study the behavior and even the methods to control it.

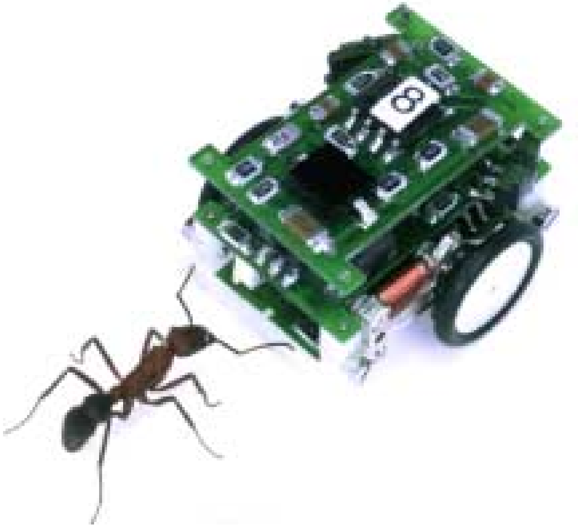

Figure 4: The size of Alice is similar to an ant.
Photo by Guy Theraulaz / CNRS - UPS - LECA Toulouse.

4. Conclusion

In this paper we have presented and discussed the scaling and limitations of mobile micro-robots (MMR). The study of the scaling effect enables a deeper understanding of the individual components and their interactions. This knowledge turned out to be very crucial for building small robots. However, the lack of small high performance motors, sensors and power sources makes the design of MMR still a big challenge. Additional research and development in micro systems technology is required to further push this fascinating field in robots.

5 References

[Garcia97] C.Garcia Marirrodriga, M.Van Winnendael, P.Putz, “Micro-Rovers for Scientific Applications in Mars or Moon Missions”, ESTEC, 1997.

[Burckhardt72] C.W. Burckhardt, “Les lois de similitude en microtechnique”, Journées de microtechnique, pp 6-19, 1972.

[Jufer95] M. Jufer, “Electromécanique”, Traité d’électricité, Vol. IX, Presses Polytechniques et Universitaires Romandes, Lausanne, 3ème édition, 1995.

[Drexler92] E. Drexler, “Nanosystems: Molecular Machinery, Manufacturing, and computation”, John Wiley & Sons, Inc, 1992.

[Wilcox97] B. Wilcox, A. Nasif and R. Welch, “Implications of Martian Rock Distributions on Rover Scaling”, Planetary Society International Conference on Mobile Planetary Robots and Rover Roundup, Santa Monica CA, 1997.

[Dario92] P. Dario et al., “Microactuators for microrobots: a critical survey”, Journal of Micromechanics and Microengineering, vol 2, no 3, pp141-57, sept. 1992.

[Fearing98] R.S. Fearing, “Powering 3 Dimentional Microrobots: Power density Limitations”, Tutorial on Micro Mechatronics and Micro Robotics, ICRA’98, 1998.

[Nicoud95] J-D. Nicoud, “Microengineering: when is small too small? Nanoengineering: when is large too large?”, Int. Symposium on Micro Machine and Human Science, pp 1-6, 1995.

[Shimoyama95] I. Shimoyama, “Scaling in Microrobots”, IROS’95, pp 208-211, 1995.

[Caprari98] G. Caprari, P. Balmer, R. Piguet, R. Siegwart, “The Autonomous Micro Robot ALICE: A platform for Scientific and Commercial Applications”, Int. Symposium on Micromechatronics and Human Science, pp 231-5, 1998.

[Caprari00] G. Caprari, K. O. Arras, R. Siegwart, “The Autonomous Miniature Robot Alice: from Prototypes to Applications.”, IROS'00, pp 793-798, 2000.

[Siegwart98] R. Siegwart, C. Wannaz, P. Garcia, R. Blank, “Guiding Mobile Robots through the Web”, Workshop Proc. of IROS’98, pp 5-10, 1998

[McLurkin96] J. McLurkin, “Using Cooperative Robots for Explosive Ordonance Disposal”, MIT AILab, 1996, http://www.ai.mit.edu/projects/ants/papers.html

[LAMI] LAMI-EPFL, Switzerland, “The Microrobots Jemmy and Inchy”, http://diwww.epfl.ch/lami/mirobots/1cubes.html

[Fukuda99] T. Fukuda, H. Mizoguchi, K. Sekiyama, F. Arai, “Group Behavior Control for MARS (Micro Autonomous Robotic System)”, ICRA ‘99, pp. 1550-1555, 1999.

[Navarro99] L.E. Navarro-Serment, R. Grabowski, C.J.J. Paredis, P.K. Khosla, “Modularity in Small Distributed Robots”, *SPIE vol. 3839*, pp. 297-306, 1999.

[Sandia01] Sandia National Laboratories, “New Release - Mini-robot research”, 2001, www.sandia.gov/media/NewsRel/NR2001/minirobot.htm

[Freese99] M. Freese, M. Kaelin, J-M. Lehky, G. Caprari, T. Estier, R. Siegwart, “LAMAlice : A nanorover for planetary exploration”, Int. Symp. on Micromechatronics and Human Science, 1999.

[Bonabeau99] E. Bonabeau, M. Dorigo, G. Theraulaz, “Swarm Intelligence: From Natural to Artificial Systems”, Oxford University Press, July 1999.