A Challenging Application in Swarm Robotics: The Autonomous Inspection of Complex Engineered Structures

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Swarm robotics is a relatively new paradigm for the coordination of multiple robots solely based on local interactions using simple individual robotic nodes. Originally inspired by the intriguing capabilities of natural swarms such as termites, wasps, and ants which are capable of complex tasks such as nest building, brood sorting, or routing for optimal foraging, swarm robotics has the potential to become a full-fledged engineering discipline.
Research in swarm robotics is still in its infancy, however, and the main question of how to design an individual robot for achieving a desired behavior on the swarm level is still unsolved to a large extent. This, together with the engineering challenges associated with building robust autonomous miniature robots, has so far prevented swarm robotics from finding concrete commercial applications.

Turbine Inspection
A potential application is the inspection of complex engineered structure such as turbines from the inside [1] (Figure 1 and 2). Turbines are the critical element in power plants and jets, where they face extreme wear and tear. Down-time however leads to considerable cost and safety problems. In order to ensure economical and safe operation, turbines need to be inspected visually using borescopes at regular intervals – a process that might be handled automatically in the future, for instance by embedding self-actuated sensors that perform inspection when the turbine is idle.
Developing such a system comprises three engineering thrusts: miniaturization of sensors and actuators, control of distributed hybrid systems, and sensor fusion for providing information to a human operator. All three domains are limited by the necessary miniaturization in terms of energy, sensing, actuation, and computation, which in turn rules out certain control approaches – in particular those that require rich sensor information and perform extensive reasoning. This requires in turn departure from common engineering ground and investigation of algorithms from a probabilistic perspective, where discrete robot controllers (Finite State Machines) and continuous distributions (Probability Density Functions) form a distributed hybrid system. Finally, commands by human users that address properties on the swarm level need to be synthesized into control inputs to the individual robots.

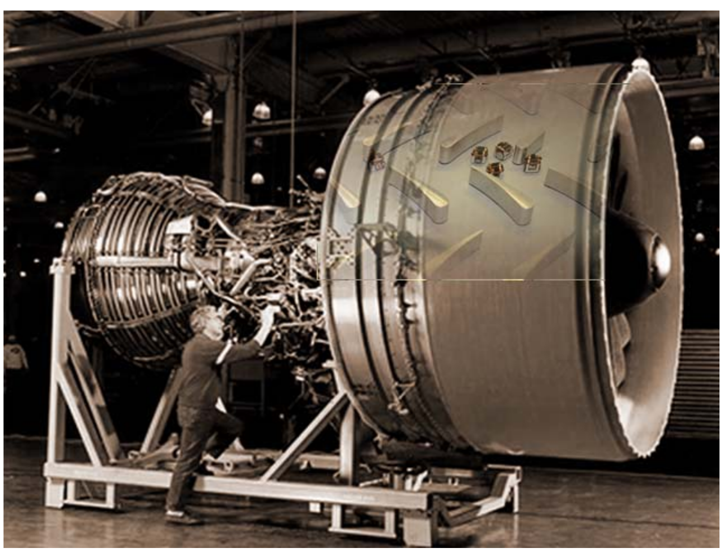

Figure 1. A photo montage of a Pratt&Whitney PW4000 turbo-fan engine and the 2D mock-up system used at the Swarm-Intelligent System group. The location of the superposition indicates the targeted section of the engine to be inspected.

Notice that our research currently does not take into account the upside-down locomotion problem imposed by a real, cylindrical turbine. There exists however miniature robots that successfully solve this problem using magnetic or sticky wheels, and various researchers are currently investigating bio-inspired fibrillar structures such as those that can be found on the feet of Geckos. Moreover, the inspection task is highly parallelizable and any multi-robot solution implies considerable speed-up.

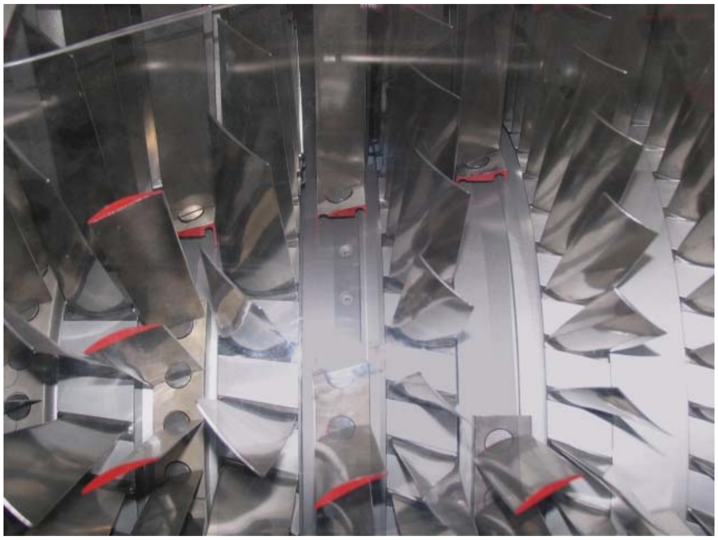

Figure 2. A close-up on the compressor section of a medium-size jet turbine engine. The distance between blades is approximately four centimeters.

Experimental Setup

Sponsored by the Swiss National Science Foundation, the Swarm-Intelligent Systems Group at the École Polytechnique Fédérale Lausanne developed a test-bed involving 40 custom-made miniature robots operating in a simplified 2D turbine environment (Figure 3), which can be analyzed by an overhead vision system[1]. Although aiming to eventually prototype a real turbine inspection system, experiments conducted so far rather contribute to the development of a general methodology for formal analysis and synthesis of swarm-robotic systems. Besides being necessary milestones, these findings cross-fertilize the development of other potential application domains for swarm-robotic systems (coverage, surveillance, and search tasks, for example). In particular, we were able to show how the modeling and design process of a swarm-robotic system can be assessed using standard automatic control methods, namely system identification [2] and optimal control [3], respectively.

Hardware development

Designing a self-locomoting platform that fits the size constraints imposed by the turbine environment (inter-blade distances less than a few centimeters, see Figure 2), while providing sufficient sensing and communication sub-systems for inspection and reporting, is still a major challenge. The *Alice*, a miniature robot (2cm x 2cm x 2cm) driven by two watch motors and endowed with four infra-red sensors for obstacle avoidance (3cm range), was developed by G. Caprari at the Autonomous Systems Laboratory, EPFL (now located at ETH Zürich) and serves as a baseline for our system. We developed a 2.4GHz wireless, ZigBee™-compliant, radio module that is controlled by a dedicated CPU running TinyOS, an emerging operating system standard for wireless sensor networks[2] (Figure 4). In integrating radio communication into a small platform such as the *Alice*, high-frequency (HF) analog design and power consumption (around 60 mW for the radio, compared to 15mW for basic operation of the robot) are major challenges. Currently, we are also prototyping a camera that will occasionally transmit low resolution images (30x30 pixels, RGB color) to a supervisor computer. Also here, energy consumption is the bottleneck as the onboard battery of the *Alice* is only providing around 90mW peak, and thus prohibits the concurrent use of motors, radio communication, and camera. The hardware architecture, which fits well into a volume of 2cm x 2cm x 3cm (including motors and battery) is summarized in Figure 5.

[1] http://swistrack.sourceforge.net
[2] http://www.tinyos.net

System analysis and synthesis

In order to derive properties such as stability and completeness of the coverage process, analytical models for describing swarm performance are necessary. Unfortunately, swarm robotics cannot be analyzed using “classical” methods due to its distributed nature and the large amount of noise (from inaccurate sensors and minimalist hardware actuators).

Figure 3. A simple 2D mock-up of a turbines interior, which allows us for modeling and designing swarm coordination, independently from the upside-down locomotion problem. Image © Alain Herzog.

We tackle this problem by modeling on the one hand the (probabilistic) population dynamics of the swarm, i.e. the average ratios of robots within a certain state, and on the other hand the spatial distribution of the swarm in the environment in terms of a spatial probability density functions. Model parameters are determined by a system identification process [2], which consists of analysis of experiments involving one or several robots. The resulting system of difference equations can then be used for predicting the behavior of the entire swarm, and can consequently be used in a model-based/optimal control framework. Whereas promising results exist that formulate the swarm-robotics control problem as an optimal control problem, analysis of such systems is still in its infancy and further research in this direction is necessary.

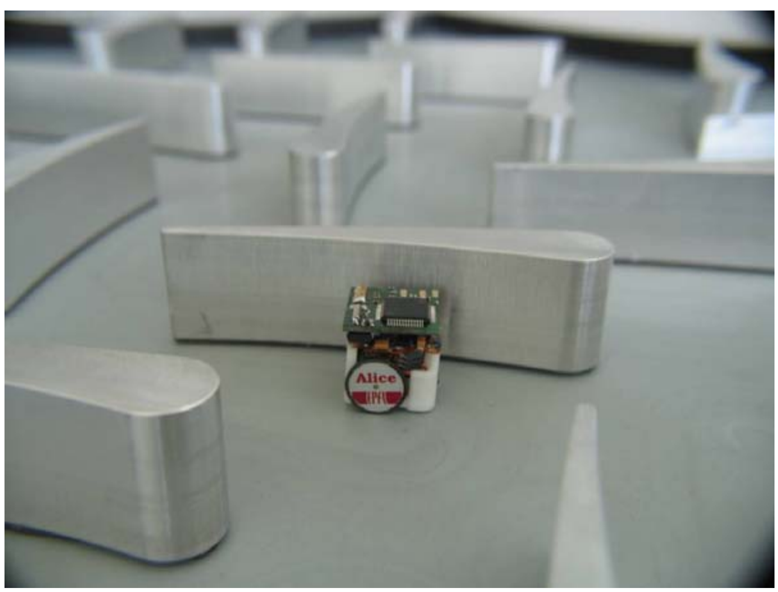

Figure 4. The miniature robot Alice endowed with a 2.4GHz wireless communication device.

Human-Swarm Interfaces and Sensor Fusion

In order for humans or high-level agents to interact with a swarm as a whole without bothering about the individual control of its members, techniques have to be developed which provide this synthesis automatically. In the inspection case study, individual agents form a network of sensors whose data needs to be fused and presented to the user as if read from a single sensor (i.e. snapshots of the turbine's interior). On the other hand, tasks have to be defined in terms of swarm rather than individual behavior, raising the need for synthesis methodologies for generating individual behaviors out of given complex behaviors at the collective level. For instance, a task might be defined in terms of the sensor coverage to be achieved, leading to closed-loop control based on the actual sensor coverage of the swarm.

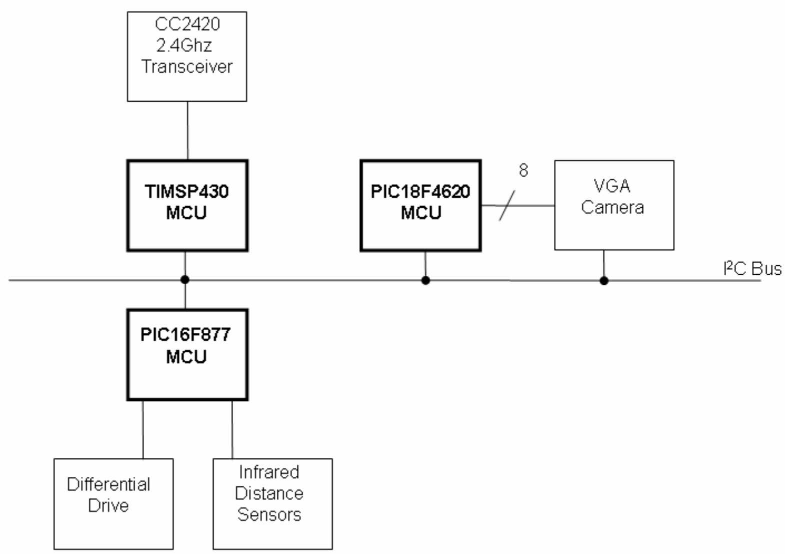

Figure 5. Block-Diagram of the inspection platform endowed with 2 watch motors for differential drive, a 2.4GHz ZigBee^{TM}- compliant wireless radio, a VGA camera, and three microcontrollers connected by an I^2C two-wire bus.

Although the individual robots are not able to localize themselves in the turbine environment, we are planning on exploiting the measurements of the distance sensors as well as the odometry readings of each robots in order to reconstruct every robot's trajectory in the a priori known environment. Then, images recorded by the robots can be mapped on a CAD model of the turbine, eventually leading to a complete, three-dimensional snapshot of the turbine's inside.

Conclusion and Outlook

Although commercially available swarm-robotic inspection systems are still dreams of the future, on-going research is able to push the boundary of robotic miniaturization, analysis, and control. These findings in turn might enable other applications for swarm robotics, where constraints are less severe, such as inspection of cargo holds, tanks, or industrial facilities, where inspection by a robot swarm might soon become reality.

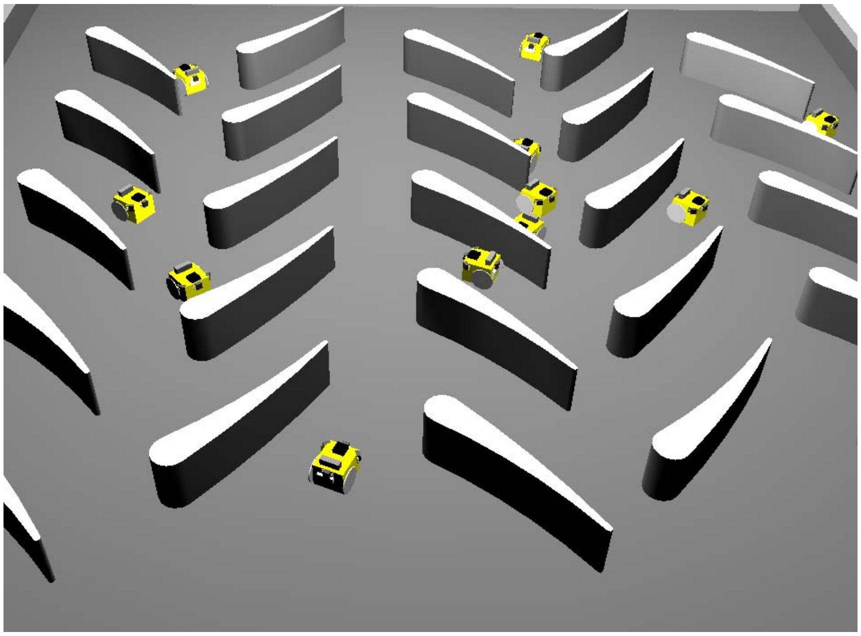

Figure 6. Realistic, sensor-based simulation in *Webots* (Cyberbotics S.a.r.l., Lausanne). *Webots* allows us to explore particular sensor and actuator configurations prior to implementing them in real hardware as well as gathering systematic experimental data for validating system modeling and identification.

References

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[3] Correll N. and Martinoli A., “Towards Optimal Control of Self-Organized Robotic Inspection Systems”, *Proc. of the Eight IFAC Int. Symp. on Robot Control*, September 2006, Bologna, Italy, paper No. R-035.