MagneBike - Toward multi climbing robots for power plant inspection

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ABSTRACT

An ever-growing infrastructure, including existing and newly built power plants, as well as a rising environmental awareness in society call for inspection and maintenance systems of high efficiency. A solution can be found in the development of mobile agents to provide assistive inspection tools with improved autonomy. In collaboration with industry the MagneBike robot for power plant inspection has been developed. The robot has been tested in a specific real field environment showing critical issues but inspiring future guidelines. This paper proposes to turn the semi-autonomous MagneBike robot into a multi-agent inspection system with clear benefits in speed, robustness and flexibility of task execution. The inspection task is approached by a hybrid coverage method that combines the concepts of blanket and sweep coverage. Three algorithms implementing hybrid coverage are presented and evaluated in simulations.

Categories and Subject Descriptors

I.2.9 [**Artificial Intelligence**]: Robotics—*Autonomous vehicles, Commercial robots and applications*; I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*Multiagent systems, Intelligent agents, Coherence and coordination*

General Terms

Design, algorithms

Keywords

Inspection robot, distributed coverage, multi-robot systems

1. INTRODUCTION

Many existing power plants are reaching the end of their designated lifespan. Aging, corrosion and mechanical stress cause structural damages and lead to leakages in the construction. Inspection and maintenance allow for early detection of defects and prevention of massive damages on installations or of supply shortfalls, and guarantee safe operation of industrial plants for the future years. Periodic inspections of fossil and nuclear power plants are prescribed in safety and environmental regulations and are required by law.

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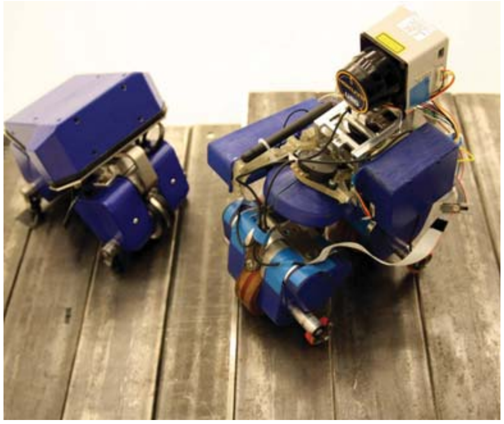

Figure 1: Two MagneBike robots, one equipped with a 3D laser scanner.

Inspection of industrial systems involves the risk of disassembly damage and high cost due to the outage of the facilities during the inspection procedure. *Non Destructive Testing (NDT)* enables the inspection of the industrial structures without causing damage. Current NDT inspection systems include hand-held devices and more recently teleoperated mobile systems for inspections directly in the structures. So-called *in-situ* inspection reduces the outage duration. Visual inspection, Eddy-current and ultrasonic testing are among the approved sensing methods commonly used for NDT.

In order to cope with the increasing need for inspection and maintenance, efficient, reliable and user-friendly inspection systems must be provided. Selling points are: 1) *Efficiency and safety.* Automated systems must be as reliable as traditional systems. Well-engineered systems can improve both accuracy and robustness in the workflow (e.g. by a fusion of measurement data or reduction of human errors), and offer superior cost-efficiency to enable regular inspections. 2) *Ease of use.* To date, most inspection devices must be guided manually over the structures to cover the surfaces completely. These procedures require accurate professional skills and are time consuming. But industry lacks in experienced inspectors, thus human experts should only be needed for analyzing the inspection results. 3) *Accessibility.* Certain parts under inspection are not reachable by the inspectors

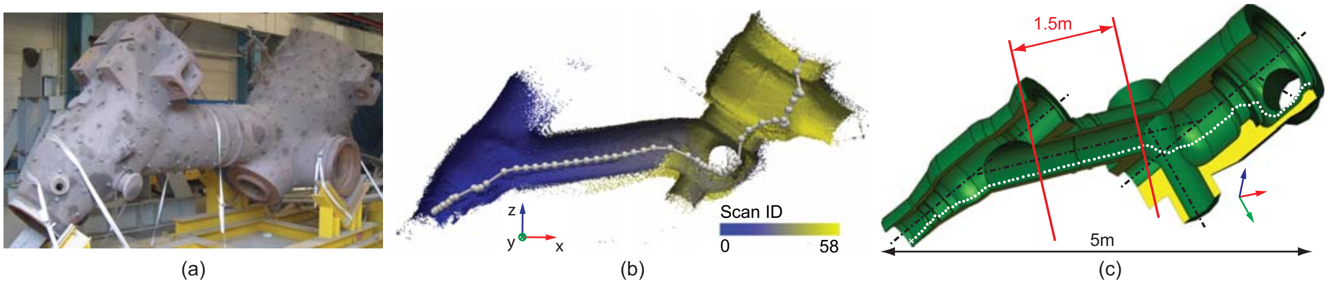

Figure 2: (a) The steam chest environment. (b) The 3D point cloud reconstruction generated from laser scans (cut view). MagneBike moved along the gray path (scanner frame) during exploration. (c) An approximate CAD model of the steam chest and the followed path (wheel frame).

without risk or great difficulty. 4) *Unknown structure*. Even if a structure can be accessed with the probe, the inspector's view might be occluded and an exact construction plan (2D drawing or 3D model) is usually not available.

Automated inspection systems are subject of current research (see Section 2) and have not yet reached sufficient level of industrialization. The Autonomous Systems Laboratory at ETHZ/EPFL and ALSTOM Power Services have been collaborating in a CTI-funded project[1] for several years to work toward the application of autonomous mobile agents in power plant inspection. The project involved professionals and experts from the power plant business as well as roboticists. In a first stage the focus was on the design of a single agent, the *MagneBike* inspection robot (Figure 1), that can climb and localize itself in complex 3D structures. The operator is assisted with low-level control running onboard and 3D visualizations of the environment on a remote computer during teleoperation. Now, the second stage has the goal to extend the system to a team of five robots that can independently achieve tasks by cooperation.

The paper is organized as follows. First we give an overview of related work by discussing selected approaches relevant to robotic power plant inspection. Then the MagneBike robot, locomotion and localization concepts as well as the system architecture are presented in Section 3. A short description of the inspection tasks for a typical industrial installation follows in Section 4. In Section 5 the required extensions to build a multi-agent inspection system are described. Multi-robot coverage algorithms, which will be implemented on a team of MagneBike robots in the future, are analyzed in simulations. Finally, we conclude with an outlook on the next development steps.

2. RELATED WORK

Mobile inspection and maintenance robotics research covers a broad range of applications. Robotic inspection systems have recently been developed with the aim to inspect industrial installations and power plants, from boilers [13] to steam turbines [5] and generators [8]. Such inspection is challenging and solutions must be found at the intersection of different fields in robotics, such as robot locomotion, localization, navigation and sensing.

Regarding locomotion, if the environment is ferromagnetic, the most common solutions are systems based on magnetic devices. Magnetic adhesion can be achieved through walking-type systems with electromagnetic devices in their feet, such as inchworm robots [12], through magnets in the robot structure or caterpillars [19] as well as magnetic wheels [9, 14]. In the context of power plant inspection, systems that rely on electromagnets are unfavorable in general because they require advanced control and do not ensure security against falling in case of failure of the system's power source. Wheeled systems with permanent magnets are more robust and simpler, and allow for continuous motion on smooth or slightly curved surfaces. However, wheeled robots are typically limited with respect to obstacle negotiation, which makes their application in industrial structures difficult.

Another research area addresses the localization techniques to be used in the inspection systems. Localization concepts depend on the robots' sensing and processing capabilities, on the characteristics and prior knowledge of the environment as well as the level of decentralization in the system. An example of a well advanced system that embeds sensors to construct detailed 3D maps of the environment, locates itself in the map and drives autonomously is the Groundhog robot designed to explore abandoned subterranean mines [22].

Extending from a single to a multi-robot system opens up yet another research field. [15], [3] and [10] are exemplary approaches for multi-robot exploration that point out opportunities and challenges arising when several robots are involved in the localization and mapping process. The survey [4] provides an overview of early approaches in robotic coverage. Since then many works, especially from the multi-robot community, have focused on the coverage problem. But only a few contributions deal with inspection and maintenance by a real robot team, as required for power plant inspection for example. In [5] a robot swarm is tested in a jet turbine mock-up to perform collaborative inspection of the compressor blades. Robotic sensor agents for ultrasonic NDT of industrial structures are developed in [9, 7], with the main interest on the reconfigurability of a multi-agent system and its use to a robust and adaptable distributed scanner.

Aforementioned inspection systems mostly include small size climbing robots with high mobility without integrating localization and mapping sensors, or conversely, systems with advanced 3D localization and mapping ability but with limits in climbing mobility, being either too large or heavy.

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[1] The Commission for Technology and Innovation (CTI) is the Swiss confederation's innovation promotion agency. CTI fosters knowledge and technology transfer between companies and universities by bringing them together as partners on applied research and development projects.

To the best of our knowledge, a small size climbing robot, as MagneBike, incorporating high climbing mobility, 3D localization and mapping to operate in complex shaped possibly unknown environments has not been reported in the literature. The final objective of the CTI-project is to deploy MagneBike in a multi-robot system to take the innovation even a step further.

3. AUTOMATED INSPECTION

A first goal of the CTI-project was to design a mobile agent that is adaptive to many different scenarios and brings NDT sensors to any location in the environment. Diverse locomotion and attachment principles were investigated. As industrial structures are ferromagnetic environments, wall climbing robots that use magnetic wheels for adhesion are found to be a promising solution. In this framework, the compact and mechanically simple MagneBike robot [20] was developed (Figure 1).

The robot consists of two magnetic wheel units in a motorbike arrangement with integrated lateral lever arms. These arms have two complementary functions: they can be used to slightly lift off the wheel in order to locally decrease the magnetic attraction force when passing concave edges or to laterally stabilize the robot when gravity is unfavorable. Steering is ensured by an active degree of freedom on the front wheel and surface adaptation is provided by a free joint on the fork. This locomotion concept has a very high mobility and allows to drive on complex 3D industrial environments that are not foreseen for robots. The robot can climb vertical walls, follow circumferential paths inside pipe structures and can also pass over complex combinations of convex and concave step obstacles with almost any inclination regarding gravity. It requires only limited space to maneuver because turning on spot around the rear wheel is possible. For a detailed characterization of the locomotion concept and mobility refer to [20].

In order to track and control the robot in a confined environment, such as a tube-like structure (see Figure 2(a)), a 3D localization and mapping concept has been developed and implemented on the robot. The localization strategy consists in combining 3D odometry with 3D laser scanning and matching. 3D odometry is used to continuously track the robot position on the surface between the locations where 3D scans are taken. The registration of 3D scans using the Iterative Closest Point (ICP) algorithm [1] allows to build 3D global maps of the environment in which the robot is moving (Figure 2(b)). Details about the localization and mapping strategy and its characterization through field experiments can be found in [21].

The compact and lightweight climbing robot (185 × 143 × 235 mm, 3.3 kg) features five actuators for locomotion, many different sensors (e.g. strain gauges, encoders, a 3-axis accelerometer, a 3D laser scanner), electronic modules and a single board computer as shown in Figure 3. The onboard electronic modules are dedicated to low-level tasks, such as the motor control or the 3D scanner control, while the onboard computer controls local processes involving embedded sensors and direct interaction with the environment or predefined movements. MagneBike for instance controls behaviors such as the deformation control that avoids robot deformations when driving on irregular surfaces and the control of the stabilizer arms for lateral stabilization. Processes requiring a lot of computation power (e.g. scan matching, 3D visualization tools) are however running on a remote computer. High-level control decisions are taken by the human operator who is assisted by the visual feedback, the 3D scans as well as the localization of the robot in the 3D map.

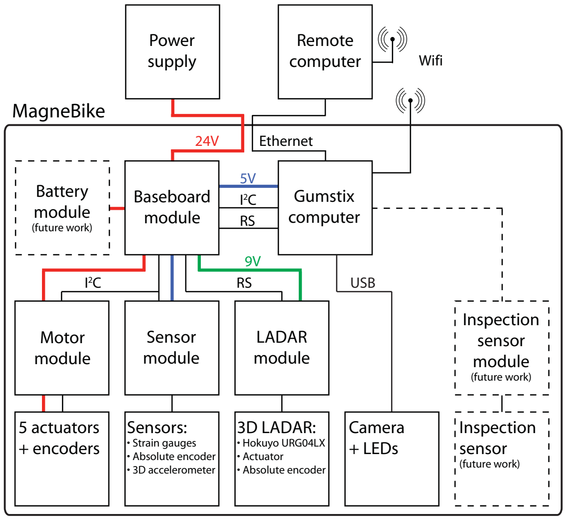


Figure 3: System architecture of the MagneBike robot. Planned modules are shown in dashed lines.

4. INSPECTION TASKS

An example for a specific structure that needs to be inspected in a power plant is the steam chest, a tube-like supply structure for the turbine (Figure 2(a)). The inspection of the inner casing of the steam chest serves as case study within the CTI-project. Before inspection, the steam chest is put out of service and is prepared; it is accessed through an opening and the MagneBike robot, or a robot team respectively, is installed at the initial position. There are different inspection tasks that can be executed, both in the single and multi-agent scenario.

In an *exploration task* the unknown structure is scanned and a full 3D map is generated (see Figure 2(b)). In a further processing step, an approximate 3D model or surface mesh can be retrieved from the 3D point cloud representation. Such a global map is a useful input for a subsequent *coverage task*. The coverage task is the actual inspection where the robot moves a probe over the surface to search for cracks. The exploration task can also be included directly in the coverage task, i.e. coverage and exploration are run simultaneously in an unknown environment. Other tasks might be possible, such as a *repair task*, where the robots treat a defect in case of maintenance. Once the tasks are completed, the operator removes the robots from the steam chest and places them in another section or part to start the next inspection.

We verified our approach on the basis of the exploration task conducted in a real steam chest with a teleoperated MagneBike robot. Field experiments are very instructive as they give new insights and help identifying technical challenges that have to be met in the future. Although MagneBike is able to negotiate a broad varity of geometries, there are certain areas that are more difficult to pass. For the aim of robustness and safe operation intelligent motion planning algorithms are needed in order to select paths that avoid those critical areas. Sensors' failure rate is another safety issue that has to be addressed with redundant sensing and failure detection. Our localization method generally works well but precision and robustness of localization remain challenging. Particularly as complete coverage of the surface must be guaranteed by using probes with sensor footprints in the centimeter range, effective control strategies must be developed to automate navigation.

5. MULTI-AGENT SYSTEM

The second stage of the CTI-project has the goal to extend the inspection system to a team of five MagneBike robots that can independently achieve tasks by cooperation. Multi-agent systems allow for faster execution of tasks, increased robustness and flexibility due to parallelism, redundancy and decentralization.

In this section we focus on the coverage task. Distributed control laws must be developed to deploy multiple agents in an optimal sensing configuration and guide them over an area in a complete covering path. Here we assume that each agent can localize itself in the 3D pipe structure with respect to a global map and neighboring agents can communicate their positions. The map is generated from laser scans as described in Section 3 and 4, either simultaneously during the covering of the environment or in a prior exploration task executed by one or several agents.

5.1 Hybrid coverage algorithms

Our approach to achieve the coverage task combines deployment ("blanket coverage") and sweeping motion ("sweep coverage") of a robot team, what results in a *hybrid coverage* method. Hybrid coverage can be realized in two ways. Method 1: The agents spread out locally to cover the area while interaction keeps them in formation. The whole formation or several groups of such formations sweep over distinct regions of the environment on the high-level. Method 2: First the agents cooperatively deploy within communication range and assign areas of operation to each other, which results in a cell decomposition of the area. Then each agent takes care of its partition locally and sweeps over the cell.

We performed an in-depth study on the state-of-the-art in distributed robotic coverage with regard to feasibility for our industrial application. As a result, three algorithms were selected and further analyzed by simulations (see Subsection 5.2).

Swarm-based coverage. The first control algorithm is a reactive approach that conforms to method 1. It is loosely based on [11] and inspired by [18]. The agents map locations, which they have already covered, using a grid representation and continuously scan the grid in order to determine the optimal moving direction. The number of uncovered cells in each direction within a maximum scan radius is calculated (direction count). Directions which make the agents leave the group or result in collisions with other agents are valued lower, whereas directions which are close to the current moving direction or point into the main sweep direction of the group get higher weights. Weighting is realized by multiplying the direction count with a Gaussian distribution. The mean represents the desired direction an agent should be attracted to, the standard deviation represents the intensity of attraction. The agents should achieve coverage as a group. Our algorithm uses the concept of the *main sweep direction* to force the agents to move in the same direction and follow a common sweeping path. The main sweep direction is regularly updated by the agents. The agents record the uncovered cells in every direction over a certain time frame and finally agree on the direction with most uncovered cells as new main sweep direction.

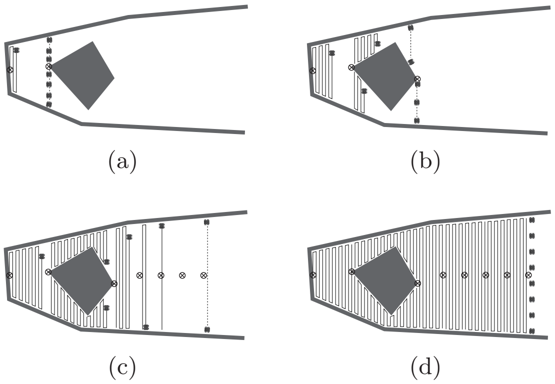

(a) (b) (c) (d)

Figure 4: Robotic band coverage. (a) One agent is left behind at the START critical point to cover the first cell. (b) The group of agents separated at an IN critical point. The subgroup on the bottom detects an OUT critical point. (c) The two subgroups reunite. Once the area becomes too large, a new MIDDLE critical point is set. (d) The agents gather at the last remaining critical point and start over again.

A set of simple rules gives the utility of each direction for the agents: "the expected area to cover is maximized", "the robots avoid collisions but stay together in a flock", "the change in moving direction is kept low while motion in the main sweep direction of the group is encouraged", and "the closest cells to the robot get priority first". Finally, the next moving direction of an agent is chosen after the direction count has been calculated and scaled by the rules above.

Robotic band coverage. The second control algorithm is more deliberative, it relates to method 2 and generates an exact cellular decomposition in the manner described by [17] to cover the area. Two agents limit the work space of the entire robot team on the left and on the right side along the main sweep direction. All the other agents line up in-between. The agents move in parallel formation and spread out on the search for critical points. Critical points define the boundary of adjacent cells in the decomposition. When a critical point is detected, an agent is assigned to the cell and left back to perform sweep coverage in its cell. By leaving agents behind for coverage, a robotic network is deployed across the area over which information can be communicated among the agents (see Figure 4).

We distinguish five different types of critical points. The START critical point is set at the initial position of the agents. The IN critical point is instantiated when the group of agents is separated by an obstacle and line-of-sight between agents gets lost. The MIDDLE critical point occurs when the distance to the previous critical point exceeds a given maximum distance (to prevent loss of communication between the agents) or when the spanned cell area becomes equal in size to the area of previously created cells (to realize equal partitions). The OUT critical point terminates an obstacle and is set by an agent after following a boundary and suddenly moving against the main sweep direction. The END critical point results when two agents follow the boundary of the environment and finally meet each other. As representation of the critical points we use the notion of the Reeb graph [17]. The Reeb graph keeps track of the critical points, the cells that connect them as well as the cells that have been covered. Each agent updates its own Reeb graph as soon as a new critical point is detected.

At the point where only two agents are left (as all the other agents are already deployed), the remaining two agents move forward until three further critical points are established, two of which outline their upcoming coverage work and one additional critical point which serves as starting point for a new task. Tasks (e.g. "sweep through cell") are directly linked with the critical points and are kept in a task protocol. When an agent completes the coverage of its cell, it requests the next task from the task protocol and moves to the starting point of the newly assigned task. As soon as the number of agents gathered at the starting point enables the execution of the new task, the agents start again with the coverage procedure.

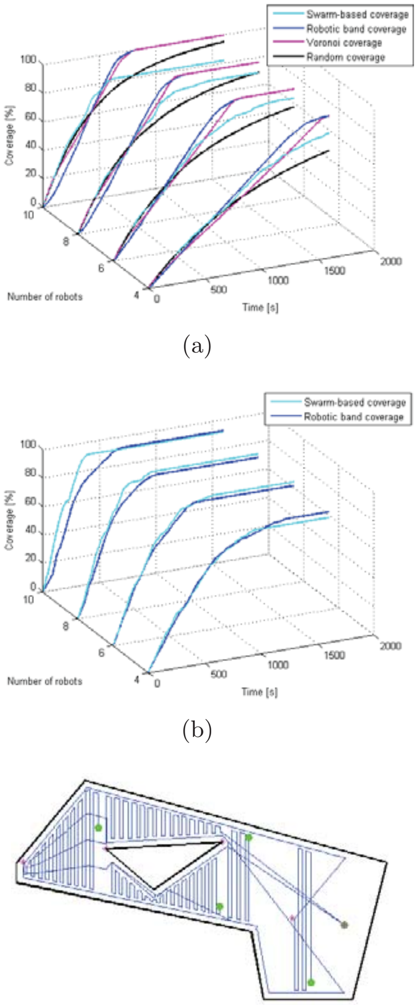
Voronoi coverage. The third control algorithm also implements method 2 and combines benefits from the first two approaches. It features characteristics of swarm-based methods like robustness, adaption and emergent behavior, but still remains coordinated and is mathematically defined by a gradient optimization approach [6]. The robot team is distributed in an optimal configuration over the area by minimizing the average distance to the nearest locations for each agent, i.e. by minimization of the overall energy

$$\mathcal{H}(\mathbf{P}) = \sum_{i=1}^{n} \mathcal{H}(\mathbf{p}_i) = \sum_{i=1}^{n} \int_{V_i} f(\|\mathbf{x} - \mathbf{p}_i\|)\ \phi(\mathbf{x})\ d\mathbf{x}\ , \qquad (1)$$

where V_i denotes the Voronoi region with the agent i as generator. Function $\phi(\cdot)$ in equation (1) is a weight or density that describes the importance of the locations in the area. Function $f(\cdot)$ is a strictly increasing function of the distance to a point in our scenario [2]. The algorithm drives the agents successively to the centroids of their Voronoi cells and thus generates a centroidal Voronoi tessellation (CVT), which was shown to locally minimize the objective function in equation (1). After the agent configuration has converged to a CVT and the space is partitioned, each agent covers its cell by a sweeping motion (see Figure 6(a)).

5.2 Evaluation of algorithms

We implemented the three proposed coverage algorithms in Matlab. We analysed the algorithms on the basis of two different polygonal environments (both with overall dimension of 3 x 5 m), a simple rectangular area and a non-convex area with a single triangular obstacle in the center, as shown by the simulation visualizations in Figure 6(a) and Figure 5(c). The agents move with a fixed speed of 5 cm/s and their sensor footprint covers a circle with radius 3 cm. The agents are assumed to be point robots, thus there is no collision avoidance included in the simulations [3]. The agents are holonomic and able to move in any direction. This assumption is in accordance with the MagneBike robot, as MagneBike can turn on spot to align with the new direction. However, the bicycle kinematic of MagneBike must be considered in the future to achieve superior performance for coverage. The simulation is ideal in that no noise or physics (e.g. friction) are included and perfect localization is assumed. The focus is clearly on the algorithm behavior and the coverage paths generated in order to gain a first understanding for the usefulness of the proposed approaches.



(a)

(b)

(c)

Figure 5: Comparison of coverage algorithms. Coverage over time for a team of 4, 6, 8 and 10 agents in (a) the rectangular area (as shown in Figure 6(a)) and (b) the non-convex area. (c) Six agents perform robotic band coverage in the non-convex area.

Figure 5(a) shows the coverage over time that results from

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[2] The lengths of the agents' paths to reach the locations within their cells from their final configuration at convergence, i.e. before they start sweeping their cells, should be minimal compared to each other.

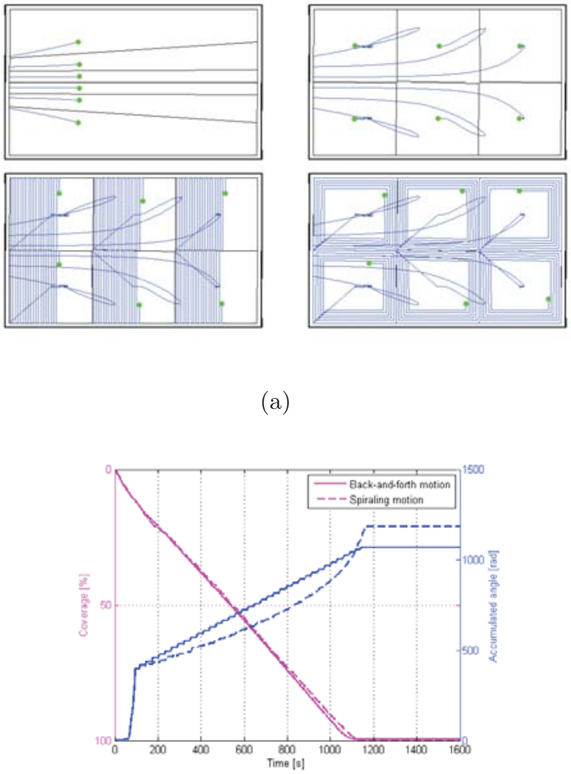
[3] In the future, the collision avoidance can be included directly in the coverage algorithm or taken over by a controller on a higher level.

simulation runs with the three coverage algorithms in the simple rectangular area and varying numbers of agents in the team. We added a simple random coverage algorithm as a benchmark, in which each agent changes its direction at random whenever a boundary is reached or another agent comes too close.

As the swarm-based coverage approach weights the direction counts depending on several rules as presented above, it needs a lot of tuning. In contrast, the maximum size of a cell to cover is one of the few parameters required by the robotic band coverage approach. The choice of the optimal cell size depends on the geometry of the environment and the number of agents. Therefore the agents should adjust the cell size automatically by sensing the environment and communicating the number of robots in the team. In the simulations, we set the maximum cell size to the optimal value for the respective number of agents and environment.

All three approaches generally outperform the random coverage algorithm. Even though our swarm-based coverage approach with limited scan radius does not guarantee complete coverage of the surface compared to the robotic band and Voronoi coverage, a final percentage of roughly 90% of coverage is reached in most cases. If no uncovered cell is within range of the whole group, the robots are going to terminate the coverage task. In order to solve this problem, the agents must consider the number of times a cell was covered rather than simply whether a cell was covered or not. The effort of methodical coverage is finally paid off when the last 20% of the area to cover are reached. We see that the approaches implementing method 2 from above perform better and cover the area faster and completely. Robotic band and Voronoi coverage perform similarly well in the rectangular area.

Although the robotic band coverage approach covers environments of simple geometries well, it highly depends on the complexity of the environment as shown in Figure 5(b) and 5(c). While obstacles in the environment are no problem for the swarm-based algorithm, unequal cell sizes are induced for the approaches of method 2. Namely in the case of robotic band coverage, the obstacles introduce additional critical points, what results in more cells, a higher number of split up robot teams and finally a higher waiting time for agents that come and help to fulfill a task. An enhanced task allocation or a task auctioning system may reduce waiting times.



(a)

(b)

Figure 6: Voronoi coverage. (a) The sequence shows six agents covering the rectangular environment by using either back-and-forth (left) or spiraling motion (right). (b) Coverage and accumulated angle resulting from the two motion patterns shown under (a), plotted over time for the total robot team.

The approaches of method 2 require the agents to sweep through the cells. We found it interesting to have a closer look at that part of the algorithms. Figure 6(a) shows several stages of the Voronoi coverage process for six agents in the rectangular area, once using back-and-forth motion and once spiraling motion for sweeping. The percentage of coverage and the accumulated angle of direction change over time are plotted in Figure 6(b). As we assumed constant speed in our simulation, the length of the agents' path grows linearly and is equal for both motion patterns, i.e. the agents need the same time to cover the cells (ideal case). After the agents are deployed, the sweep coverage begins. If the back-and-forth motion applies, the angle increases in constant time intervals by π until full coverage is achieved. In the case of the spiraling motion pattern, the accumulation of the angle starts growing slowly, becomes faster the narrower the spiral gets and finally ends in a singularity if no stop condition is applied. Turns are costly as a real robot has to slow down or consider them in its trajectory. It is a topic of future research to find ways to control the shape of a cell to adequately adjust it to the environment and the available motion patterns (e.g. spiraling motion for the inherently uniform hexagonal shape of Voronoi cells).

5.3 Application of algorithms to inspection

As the real industrial structures like the steam chest environment all form hollow 3D geometries, control laws for 2D manifolds in 3D space are required in general (and are a subject of our current research). Many coverage strategies are restricted to 2D floorplans and cannot directly be applied to 3D environments. We thus follow in this paper the alternative approach of cutting and unfolding the 3D structure to retain a planar representation with additional dependencies (Figure 8(a)). The left and right sides along the cut are actually connected and the robots can move in the unwrapped object from one border to the other through this dependency. At the moment this approach is rather limited to simple environments like tube-like structures that can be (1) approximated well with smooth geometric bodies or discretized through low-complexity surface meshes (i.e. adequate resolution, no distortion), and can be (2) appro-

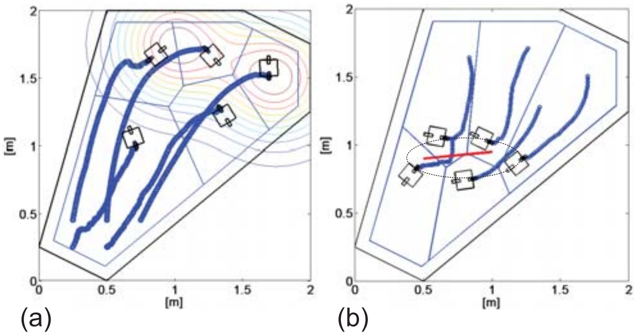


Figure 7: (a) A dense robot configuration is induced around locations where a defect is expected. (b) Once a crack (red line) is detected, the robots align to prepare for the next action.

priately segmented in 3D parts without overlap. The robot controller plans the path in 2D, then the trajectory is projected back and the robot moves accordingly in the original 3D environment.

Next we discuss the different approaches and their applicability to the inspection task of the MagneBike robots. The substantial difference in the size of MagneBike (width in the order of decimeters) and the size of the NDT sensor footprints (a few centimeters in diameter) influence the way how to cover an area. It is not possible to seamlessly cover the surface with all the robots in side by side formation. The swarm-based coverage approach adjusts the distance between the robots by setting attraction and repulsion appropriately, while the approaches based on method 2 assign every robot its own cell to provide enough space. The swarm-based and the robotic band coverage approaches both use a main sweep direction to control the overall motion of the robot team (red arrows in Figure 8(b)). The main sweep direction enables an operator to interact with the agents and direct them to different locations in the environment. Alternatively, the agents can reach a consensus on the main sweep direction taking into account the geometry of the environment (as mentioned in Subsection 5.1 for the swarm-based coverage algorithm).

The Voronoi coverage algorithm has a similar and even more versatile functionality. The density function $\phi(\cdot)$ can be used to gather robots at locations of special interest (Figure 7(a)). When running the inspection task, a human expert may identify critical locations in the structure that are experienced to fail more likely. By setting the density to higher values for those locations beforehand or during operation, the cells get smaller and the robots can spend more time for inspecting a single point, or respectively, cover the same point several times to increase robustness through redundancy. The density function also allows for formation control (Figure 7(b)). The robots can be controlled to form up along a crack for exact inspection, or maintenance in the example of a repair task. However, the Voronoi coverage approach does not result in equal partitions of the environment and its convergence to configurations of local minima is a known fact. Balancing of the workload in Voronoi coverage can be achieved by area constraints and equitable partitioning [16]. Suboptimal configurations must alternatively be addressed by a planner on a higher level of the control hierarchy. Non-convex environments are another challenge for Voronoi coverage, though recent advances show promise (the problem is addressed in [2] among others).

The swarm-based coverage approach is robust to robot failure but does not guarantee to completely cover the surface. The generated paths traverse the environment repeatedly and require to handle various positions. Even though MagneBike is able to negotiate diverse geometries, certain maneuvers are more risky and time-consuming than others and thus should be greatly avoided. The robotic band coverage approach is more prone to robot failures as agents depend on each other, execute different tasks and thus need to communicate more due to task assignment. However, shorter paths compared to swarm-based coverage are sufficient to deploy the robots in the environment. Especially rotationally-symmetric structures like tubes can be covered efficiently. This motivates the implementation of this algorithm on the MagneBike robot for industrial use. The Voronoi coverage approach falls between the first two algorithms and combines the benefits from both sides. It applies more generally, being complete and robust but less dependent on the environment geometry, what is particularly useful for applications in a priori unknown environments.

6. CONCLUSIONS

In this paper, the development process toward multi climbing robots for power plant inspection is presented. Motivated by the increasing demand for inspection and maintenance, the CTI-project, a joint project between university and industry, aims at developing inspection systems with high autonomy and efficiency. Improved inspection systems help to expand the life time of existing power plants and to prevent shortage of supply. The MagneBike robot, its application to a steam chest environment and its extension to a multi-agent inspection system is shown. Three multi-robot coverage algorithms regarding collaborative power plant inspection are developed and evaluated in simulations to establish a basis for embedding distributed coverage control on the real robots.

To overcome regulation barriers (e.g. certifications) and gain wider acceptance for robotic inspection, the system has to be continuously improved. Technical issues were identified in field experiments and are addressed in the ongoing work. Future improvements of MagneBike include the design of autonomous control, localization and navigation for 3D environments. Once achieved for the single robot, this methods will be implemented in a team of five MagneBike robots with strong focus on decentralization, cooperation and operational robustness.

7. ACKNOWLEDGMENTS

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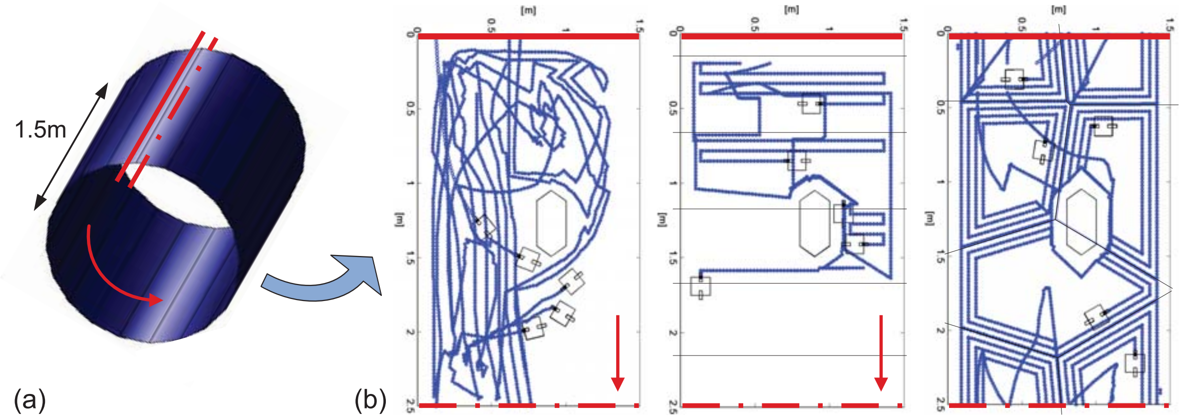

Figure 8: (a) A 1.5 m long segment of the steam chest (see Figure 2) is approximated by a cylinder which is cut and unwrapped to the plane. (b) A team of five MagneBikes is covering the surface with three different algorithms (from left to right): Swarm-based coverage, robotic band coverage and Voronoi coverage. An additional obstacle (e.g. hole, notch) was added to the environment in the simulation experiment.

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