Communication Architecture, Challenges and Paradigms for Robotic Firefighters

Sebastian Schildt Stephan Rottmann Lars Wolf

Institute for Operating Systems and Computer Networks
Technische Universität Braunschweig
Braunschweig, Germany
[schildt|rottmann|wolf]@ibr.cs.tu-bs.de

ABSTRACT

Mobile robots can be helpful for post disaster management, e.g., to explore hazardous and damaged environments. However, many challenges in various areas have to be solved, e.g., mechanical issues, situation awareness, communication capabilities. We present the interdisciplinary research project Robotic Firefighters (RFF) which addresses some of the IT problems. We take a detailed look at the proposed distributed communication infrastructure enabling communication between different autonomous mobile RFF units. Besides direct multihop communication, the RFF communication architecture includes the ability to have an RFF robot physically distribute communication nodes called *Dropboxes*. They can be used to deploy a WSN or act as data exchange points enabling communication and coordination between RFF units. Prototype implementations of the RFF *Dropbox* concept, including two kinds of *Dropboxes*, and an experimental platform for automatic deployment, are introduced.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Store and forward networks*

Keywords

Bundle Protocol, DTN, Disaster Recovery, SAR

1. INTRODUCTION

Past disasters, such as the Fukushima catastrophe, the attack on the WTC, the Gulf of Mexico oil spill, or the recent 2013 earthquake in Sichuan have shown that post disaster management tasks still require considerable human intervention, even though persons entering affected areas risk their health and lives, causing human tragedy and immense cost for national economies. With view to keeping these dangers and costs as low as possible, and to increase effectiveness of disaster management operations, the interdisciplinary research project Robotic FireFighters (RFF) has been launched by the NTH[1].

The long-term vision of RFF are teams of autonomous robots equipped with sensors, manipulators, and communication capabilities that will be able to enter dangerous, inaccessible or contaminated areas and perform post disaster tasks such as searching for survivors, evacuating injured persons, removing or securing dangerous materials and others without the need for explicit human assistance. Robotic FireFighters, in analogy to human firefighters should work together towards the common goal of getting a disaster under control.

RFF is an interdisciplinary effort between mobile robot, communication and multi-agent research. In mobile robotics simultaneous location and mapping (SLAM) in unknown and dynamic environments keeps being a challenge[8, 6]. While research on mobile robots for disaster recovery mostly focusses on singular machines[10], cooperation between different systems, especially in light of an adverse communication environment, is still an open research topic. Some theoretical results exist for specific problems such as coverage planning[13], however that model still uses a simplified line-of-sight communication model, and being a theoretical work does not concern itself with suitable technologies and protocols to cope with such challenging environments. For coordinated target tracking the question which data needs to be exchanged in order to achieve optimal performance has been considered in [17]. However, while the work addresses these important questions at least for a specific task of coordinated target tracking it does neither provide a general framework to answer these questions for other scenarios nor does it suggest how to implement the modelled communication scheme in a real system. While there has been some important work on the theoretical foundations of coordination and cooperation in multi-robot system not much has emerged in the sense of a general framework to implement those solutions, taking into account all the challenging conditions that are to be expected when implementing such systems for real.

From a high level view multi-agent research provides mechanisms for group formation and planning[14], although mostly on a much higher level than robot research is usually con-

[1]Niedersächsische Technische Hochschule, an alliance of the three universities Technische Universität Braunschweig, Technische Universität Clausthal and Leibniz Universität Hannover

cerned with. Bridging this gap is one of the goals in the RFF project. A key component in RFF to achieve this is a common model to represent information and knowledge: A distributed, resilient, versatile data structure, integrating all information, that can be used to facilitate a robot's operation as well as higher level planning. We term this the Distributed Common Information Model (dCIM). Different dCIM fragments will be exchanged between RFF units. How to get dCIM fragments transferred directly between units or in multi-hop or store-carry and forward approaches is the networking challenge of RFF. These challenges will be met by combining various established technologies, adapting the communication infrastructure to the needs of a mission. As means to this end, an important concept of RFF communication are autonomously deployable communication infrastructure units called *Dropboxes*.

In the following sections we will define a baseline scenario for RFF mission and specify what modes of communications can be used in an RFF system in Section 2. After introducing the dCIM concept in Section 3 we will detail the different *Dropbox* variants in Section 4. Finally we present some initial work creating research prototypes of *Dropboxes* and a development platform for RFF communication experiments in Section 6. Finally, in Section 7 we conclude, and discuss the next steps in building the RFF framework.

2. RFF SCENARIO

2.1 Robotic Firefighter Platforms

As the RFF project is concerned with a suitable IT framework for multi-robot systems in disaster recovery, it is not focussing on a special type of mobile gear. We assume RFF tasks to be surveying, localizing injured people and possibly measuring environmental conditions, all of which might encompass modifying the local environment, i.e. clearing obstructions. While the project explicitly addresses multi robot coordination, in contrast to existing work, we do not assume a large amount of similar platforms. Considering the costs and high specialization of current mobile robots, we assume a heterogenous mix of specialized machinery. Thus an RFF enabled robot might be a mobile ground unit using wheels or tracks. Robots might be large enough to carry people and being able to do some serious manipulation of their environment such as digging for people, or they might be as small as an RC car, solely for reconnaissance operation. Conceptually we are not limited to ground operated machines. Flying gear such as Quadrocopters might be used for surveillance. In the future large-scale walking robots are conceivable. Recently, a commercial prototype for a large-scale disaster response robot has been revealed by Toshiba[1].

With heterogenous machines, questions of coordination, team formation and task allocation[16, 12] become more challenging and important. The RFF project will provide a common framework of interoperation for heterogenous robots in RFF scenarios. While generic and integrated frameworks focussed on unifying the development of singular robots are slowly taking shape, such as the ROS platform[2], no practical general framework has yet been designed to allow for seamless integration and coordination of a group of heterogenous robots. Depending on the platform and mission profile different communication channels and paradigms are available, which will be detailed in the following sections.

[2]Robot Operating System(ROS) `http://www.ros.org/`

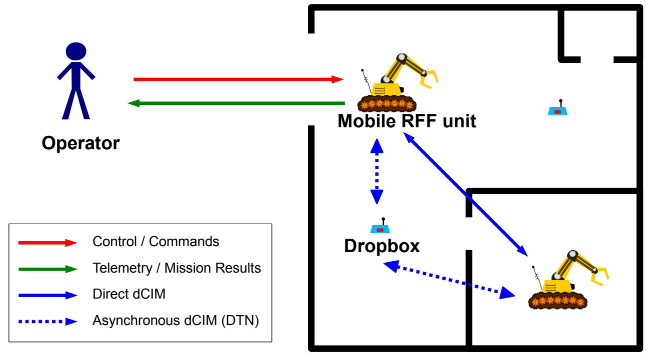


Figure 1: RFF scenario with actors and communication

2.2 Basic Scenario

Figure 1 shows a general RFF scenario with the participating entities and communication channels. Several mobile RFF units are deployed in an operation area and controlled by the operator. The operator sends commands to the RFF gear in the field and expects to receive telemetry and sensory information helping to assess the situation and support his decision-making process. How much direct control can be exerted by the operator depends on the environmental conditions and the mission profile. Under optimal conditions where a reliable, low latency, high-bandwidth link is available, direct control is possible essentially making an RFF unit a remotely operated vehicle. Autonomy on part of the RFF unit is only desired insofar, as it eases control of the vehicle, i.e. if the robot itself and its tools have too many degrees of freedom making controlling everything directly more inefficient than higher level commands. In such cases communication between RFF units is mainly needed to forward data to the operator.

However, in many situations it is to be expected that such a high quality link to the operator is not always available: The RFF units might operate inside an obstructed environment, i.e. inside a partly collapsed building with metallic structures or reinforced concrete which is effectively shielding electromagnetic radiation. Also larger operation areas, such as searching a large area in case of natural disasters such as earthquakes makes the continuos availability of high-bandwidth links more unlikely. Autonomy of RFF units becomes more important, as does communication between them: If contact with the operator might only be possible intermittently, controlling RFF units becomes more like controlling a Mars rover: Instructions are sent to an RFF unit or a group of RFF units, but neither immediate execution nor instant feedback is possible. RFF units will forward messages between each other. Data will be gathered and shared by the units in the field. All units will become data mules, and transport data in a store-carry and forward fashion until a new contact comes into range. Thus, the RFF network is effectively a Delay Tolerant Network (DTN). Communication between RFF units is necessary for the following tasks:

- Forwarding data from the operator to mobile units in a multi-hop fashion.
- Exchange sensed data and knowledge about the envi-

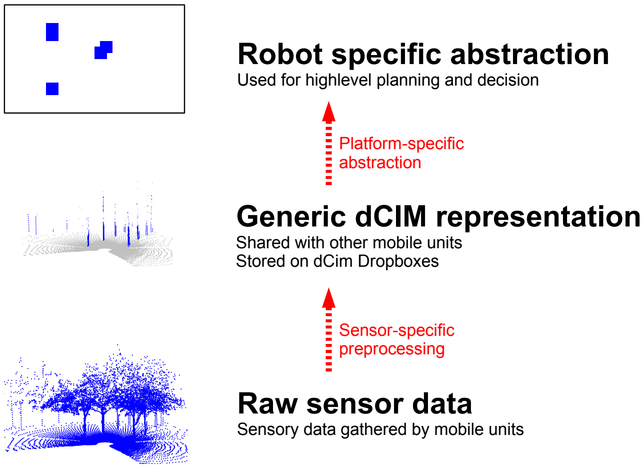


Figure 2: RFF data abstractions and the dCIM

ronment between mobile units. Data will be integrated into the dCIM which is the basis on which the autonomy and group coordination in RFF is based: An RFF unit can profit from updated data or data gathered at parts of the operation area it has not yet visited.

- Knowledge and data that is the objective of the mission: Gathered information, such as the position of injured persons, should eventually be transported back to the operator. By exchanging data, the system can make sure that information arrives at the operator as fast as possible, and that the loss of an RFF unit without communication to the operator does not mean that all gathered data is lost.

As communication between RFF units also might be impeded by the environment, a very important cornerstone of the RFF communication approach are *Dropboxes*: A *Dropbox* is an independent, battery powered communication component that can be carried, dropped and potentially picked up again by an RFF unit. Statically placed, semi-autarkic DTN relays called "throwboxes" have already been used as roadside units in a bus-based DTN network[2].

In contrast, the RFF system adopts a BYOI ("bring your own infrastructure") approach towards communication: When deemed suitable a mobile unit can deposit a *Dropbox*. Depending on the mission a *Dropbox* can help to build a fully connected network extending the operation range, or act as an additional DTN node improving asynchronous data transfer, by allowing RFF units to drop data which can later be picked up by other units. Additionally, *Dropboxes* can be used to deploy a WSN for longer-term monitoring of an area. The *Dropbox* concept is detailed in Section 4.

3. DCIM

Communication and coordination will be based on the distributed Common Information Model (dCIM) in RFF systems. While a detailed dCIM specification is out of scope for this paper, we will introduce the general idea and concept behind the dCIM.

The vision for dCIM is to offer a common, generic semantic to express concepts needed for coordination and group formation as well as formalizations of sensor data collected by RFF units. RFF units will transfer dCIM fragments between each other and store and retrieve dCIM fragments from *Dropboxes*. The dCIM will be easily (de)composable, so that every fragment is self contained and any two dCIM fragments can be fused into a larger fragment.

Raw sensor data will not be stored in the dCIM and thus the *Dropboxes*. Raw data is very specific to a sensor and needs special processing. Thus, it can probably not be interpreted by a another RFF unit based on a different platform. Additionally, for many sensors raw data will be too large to be practically shared. On a very high layer, RFF units might use different abstractions for their path planning and other high level tasks; for example they might use an occupancy grid, or extrapolate a polygon based map. Thus, the high level worldview of an RFF unit might be useless or incomprehensible to another unit. Instead of defining and forcing a specific high level abstraction for all systems, dCIM will specify generic intermediate abstractions for different classes of sensors, which do not depend on detailed knowledge of the employed sensor, and have all hardware specific processing already done by the originator. Conceptually, the dCIM will be comparable to the intermediate code used by modern compiler stacks such as LLVM[9]: All code (sensor data) is compiled to the same intermediate language (the dCIM abstraction). The intermediate code is always of the same form even though the original sourcecode might have been C++, Java, Haskell or any other language (different RFF platforms and classes of sensors). The intermediate code still has enough information attached to perform efficient optimizations and can be fed to various code generators, that output machine code for a specific kind of CPU or virtual machine. Similarly, it is easy to transform the dCIM abstraction to a platform specific abstraction used by a specific platform. This idea is visualized in figure 2.

4. RFF DROPBOXES

RFF uses an BYOI approach: In the RFF system, mobile units can place additional communication nodes. There are two main use cases for dynamically deploying communication equipment in the field.

Deploying a WSN

Consider a mission, where RFF units are searching partially collapsed buildings. While a first reconnaissance mission might take a few hours, rescue efforts will probably be an on-going effort. Continuous monitoring of environmental parameters such as vibrations indicating further collapsing or measuring of gas concentrations might be required to maximize the safety and efficiency of rescue efforts. This can be achieved deploying a WSN.

Deploying dCIM exchanges

An RFF unit can deploy *Dropboxes* to improve communication during a mission: A dCIM *Dropbox* is basically a battery powered DTN router: By increasing network coverage and storage capacity, it increases the chance of information exchange between RFF units to help with group coordination. dCIM *Dropboxes* asynchronously distribute dCIM information between RFF units. If a dCIM *Dropbox* is in range a mobile unit will deposit its current dCIM state containing sensory readings and knowledge about the environment and receive updated data deposited by other units earlier.

An experimental deployment of a *Dropbox* on a university campus with machine halls is shown in Figure 4. We used the *WSN Dropbox* described in the next section to extend the range of our mobile experimental platform (see Section 6), allowing it to send low-bandwidth telemetry to the operator. In this experiment the building prevented direct communication between the operator (1) and the mobile unit (3), even though the linear distance is only 32 m. Using a strategically placed *Dropbox* at a location accessible by the mobile unit (2), communication between the operator and the robot is possible using 2 hops, even though now the bridged distance totals 53 m.

In the following sections we describe the two types of *Dropboxes* used in RFF: *WSN Dropboxes* and dCIM *Dropboxes*:

4.1 WSN Dropboxes

As outlined above, deploying a WSN network for long-term monitoring might be part of an RFF mission. However, WSN nodes cannot only be used for deploying a WSN for monitoring purposes after the primary RFF mission, but they can also be used as control channel during the mission. Because most WSN nodes operate with low bandwidth technologies they are more robust against interference and might be better at coping with challenging communication environments than high-bandwidth technologies such as WiFi. Besides the common high frequency 2.4 GHz or 5 GHz bands many WSN communication standards can operate in the lower ISM bands such as 433, 866 or 915 MHz. These frequencies enable better penetration of solid structures. RFF units might deploy sensors like bread crumbs as "Hansel and Gretel"[3] did in the forest, to establish a stable communication line with the operator. While this will not allow for high-bandwidth telemetry to be transferred, it can still give the operator some vital influence and feedback about the mission.

Any standard WSN node whose sensors are suitable for a given task can be used as *WSN Dropbox*. It should be provided with a power source allowing for long term operation and an enclosure that offers suitable protection against the environmental hazards that are expected for a given scenario. In our prototyping applications we use the INGA sensor node[3]. It offers various sensors and integrates a LiPo charge controller that allows the usage of light high-capacity LiPo cells. For experiments a 3D printed enclosure containing the battery cell as well as the INGA node has been developed (see Figure 3(a)).

4.2 dCIM Dropboxes

RFF units can deploy immobile dCIM communication relays to facilitate better communication in the field. A dCIM *Dropbox* should contain an embedded computing platform and high-bandwidth communication abilities. It should be able to be powered by a battery for a reasonably long time. Depending on the application, energy harvesting might be possible, but a battery will work in virtually all conditions, and as we expect dCIM *Dropboxes* to be active and operating during the main part of the mission there is not much energy to be saved by duty-cycling.

As the amount of data generated by standard 3D imaging sensory even after preprocessing is quite huge, we expect a dCIM *Dropbox* to offer a couple of GiB of storage, as it needs to aggregate information from several mobile units.

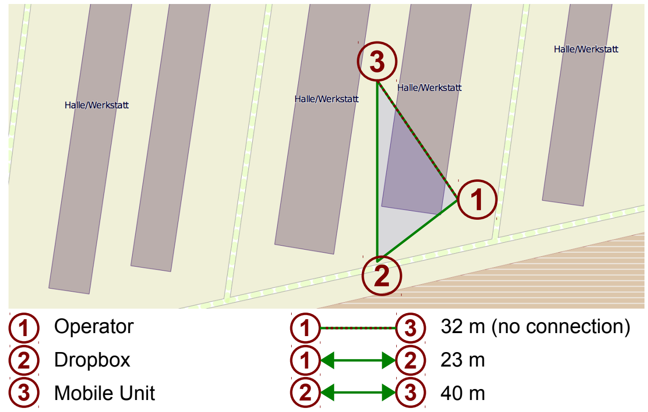


Figure 4: Dropbox deployment experiment

A dCIM *Dropbox* can be seen as introducing some form of stigmergic communication to the RFF system: Stigmergy is a concept from biology describing the mechanism of modifying the environment to proliferate information. The term has been introduced 1959 by the french biologist Pierre-Paul Grassé when examining the creation of termite nests[7]. A prime example of stigmergic communication that has also been adapted[4] and widely used in computer science[5] is the formation of ant trails: Ant trails emerge by foraging ants depositing pheromones on the path to some food source, which then reinforces other ants to do the same. Another more mundane example for stigmergic communication is a dog marking a lamp pole. In the RFF framework, every unit basically brings its own lamp poles and places them at convenient locations, enhancing the chance of exchanging information with other units.

While not strictly necessary, RFF units should have the capability to pick up *Dropboxes*, for example before retreating from an operation area. This will not only reduce waste of keeping hardware in inaccessible locations, but it will also allow moving *Dropboxes* during a mission should that become necessary. Picking up *Dropboxes* is however a mechanically much more challenging task than just deploying them. Thus, we expect some systems to leave this capability out. Using RFF's group coordination abilities, one may be able to make do with only one unit possessing the ability to retrieve *Dropboxes*.

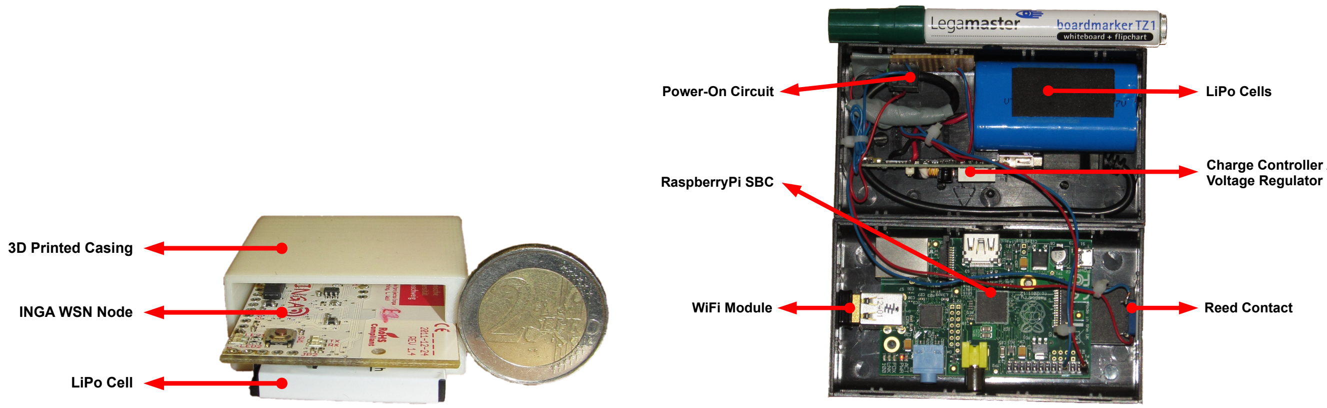
To handle the tasks outlined above we expect a dCIM *Dropbox* to be powered by a sufficiently fast CPU running a full-blown operating system. A unit along the lines of a BeagleBone[4] or Raspberry Pi[5] will be appropriate. Those platforms are powered by reasonably powerful ARM CPUs and can run Linux. In the end it depends on how much battery capacity, and thus weight and size can be afforded for a *Dropbox*, which of course is tightly coupled to the dimension of an RFF unit. However, keeping everything as small and low-cost as possible is advisable, since it will allow more *Dropboxes* per RFF unit.

5. DCIM DROPBOX PROTOTYPE

[3]Famous fairy tale published by The Brothers Grimm in 1812

[4]`http://beagleboard.org/`

[5]`http://www.raspberrypi.org/`



(a) Opened WSN Dropbox

(b) Opened dCIM Dropbox

Figure 3: Dropbox protoypes

We built a prototype dCIM *Dropbox* as feasibility study using off-the-shelf hardware. The prototype and its components are shown in Figure 3(b). It is based on a Raspberry Pi, which is a widely available ARM based mini computer that is energy efficient enough to be powered by a battery. We also equip the Pi with the RASPInga IEEE 802.15.4 shield[6] from the INGA project which allows it to act as a bridge to *WSN Dropboxes* using 802.15.4 enabled WSN nodes.

The Pi runs the IBR-DTN Bundle Protocol stack[15] to provide DTN communication capabillites. As IBR-DTN is especially designed for embedded environments, it should be easy to integrate it into virtually any robot platform. Additionally, IBR-DTN supports a IEEE 802.15.4 convergence layer compatible with μDTN, a Bundle Protocol implementation for WSN nodes[18]. This allows for even tighter integration of WSN and dCIM*Dropboxes*.

For the prototype we chose a plastic enclosure. This allows communication hardware to be put inside the box, which can then be completely sealed. It also offers weight advantages over a metal enclosure. However, when adverse environmental conditions are to be expected, more sturdy constructions are possible.

5.1 Powering

The Pi needs a 5 V power supply. Because Lithium based battery technologies achieve the highest energy densities, we choose an off-the-shelf USB power pack containing 2 LiIo cells and a charge controller as power source. In the future the cells could be replaced with higher capacity ones, and the charge controller can be replaced with a more space efficient design. LiIo cells might not be a good choice, as they are more prone to spontaneous massive exothermic existence failure than other cell types. Therefore, for some applications other battery technologies might be more suitable. Alternatively, the Boeing technique of containing the fire in a sturdy enough container could be used, and thus only a single *Dropbox* will be lost in case of battery problems.

As dCIM *Dropboxes* are much more power hungry than *WSN Dropboxes* (our prototype runs 4 hours on battery), it is not advisable to keep them running while still stored on the RFF unit. While a hybrid system with an additional low-power sensor node that is used to wake up the system[11] can be designed, we did not choose this approach for the prototype. As the Pi can already provide IEEE 802.15.4 connectivity, the additional complexity and space taken by the WSN node would not offer any benefits during operation. Instead, we developed a small circuit, that will keep the dCIM *Dropbox* powered off if a sufficiently strong magnet is placed at the outside of the box. The *Dropbox* storage on an RFF unit can be equipped with such magnets. Once deployed, the *Dropbox* will automatically power up and boot. At the moment the circuit is not power-optimized and will incur a a small power loss even when the *Dropbox* is powered off. It will drain the battery in 144 h. However, since the usable battery-life of platforms that can be used as RFF units is much lower, this does not matter. While the prototype must be opened to charge the batteries, in a future version an inductive charging mechanism would allow for a completely sealed case.

6. RESEARCH PLATFORM

As an experimental platform for testing and evaluating RFF communication systems we built a low-cost outdoor-capable experimental platform. The prototype is based on the "Wild Thumper" platform by Dagu Robotics[7]. It is a 6 wheel outdoor platform. While it is small, and for real RFF missions might be used as a surveillance vehicle at best, it offers enough carrying capacity to implement a deployment mechanism for *Dropboxes*. The current state of the experimental platform is depicted in Figure 5. We equipped the robot with a BeagleBone computer for control. The BeagleBone can communicate over WiFi or IEEE 802.15.4 using an adapted RaspINGA shield. Using the WiFi link the robot can be controlled from an Android phone. The platform can store up to 7 INGA-based *WSN Dropboxes* that can be ejected piece by piece using a DC motor that drives a spindle. A spindle nut moves a lever that will push the lowest *Dropbox* out. After the lever is retracted by the spindle, the remaining *Dropboxes* in the compartment will slide down, so that the next cycle will eject a new *Dropbox*.

[6] `http://www.ibr.cs.tu-bs.de/projects/inga/raspinga.html`

[7] `http://www.dagurobot.com/`

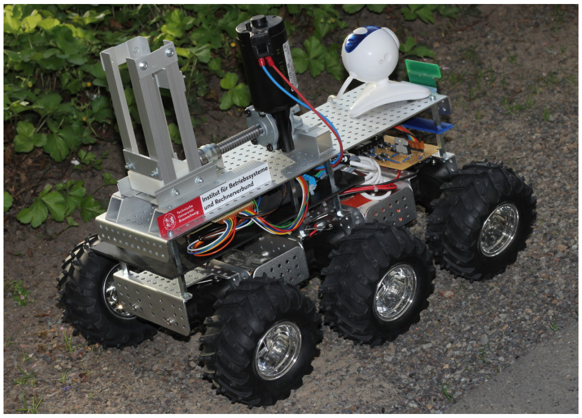


Figure 5: Experimental platform for RFF communication research

7. CONCLUSIONS AND FUTURE WORK

We introduced the interdisciplinary Robotic Firefighters (RFF) project, outlined its challenges and proposed a suitable communication architecture. Mobile RFF units will share information and knowledge using a platform-agnostic intermediate format, the distributed Common Information Model (dCIM). We use DTN technologies to share dCIM information, because DTN technologies, such as the Bundle Protocol, can scale from intermittent low-bandwidth communication to reliable high-bandwidth links. We introduced *Dropboxes*, a concept for autonomously deployable communication infrastructure. In RFF scenarios, RFF units can use *Dropboxes* to deploy a WSN network or to increase capacity of the DTN backbone. We presented prototype implementations of WSN and dCIM *Dropboxes* as well as a mobile robot platform carrying a mechanism capable of deploying WSN *Dropboxes*.

In the future we will optimize the designs of the prototype *Dropboxes* and extend the deployment mechanism to support both WSN and dCIM *Dropboxes*. The RFF project will research suitable deployment strategies for *Dropboxes* and study the resulting network performance and efficiency of the distributed system carrying out its tasks.

8. REFERENCES

[1] Toshiba Develops Tetrapod Robot for Tokyo Electric Power Plant Fukushima No.1 Nuclear Power Plant. Press Release, 11 2012. Toshiba Corporation.

[2] N. Banerjee, M. D. Corner, and B. N. Levine. Design and Field Experimentation of an Energy-Efficient Architecture for DTN Throwboxes. *IEEE/ACM Transactions on Networking*, 18(2):554–567, Apr. 2010.

[3] F. Busching, U. Kulau, and L. Wolf. Architecture and evaluation of INGA an inexpensive node for general applications. In *2012 IEEE Sensors*, pages 1–4. IEEE, Oct. 2012.

[4] M. Dorigo and G. Di Caro. Ant colony optimization: a new meta-heuristic. In *Proceedings of the 1999 Congress on Evolutionary Computation-CEC99 (Cat. No. 99TH8406)*, pages 1470–1477. IEEE.

[5] M. Dorigo and T. Stützle. *Ant Colony Optimization*. Bradford Books, 2004.

[6] C. M. Gifford, R. Webb, J. Bley, D. Leung, M. Calnon, J. Makarewicz, B. Banz, and A. Agah. Low-cost multi-robot exploration and mapping. In *2008 IEEE International Conference on Technologies for Practical Robot Applications*, pages 74–79. IEEE, Nov. 2008.

[7] P. P. Grasse. La reconstruction du nid et les coordinations interindividuelles chez bellicositermes natalensis et cubitermes sp. La theorie de la stigmergie: essai d'interpretation du comportement des termites constructeurs. *Insectes Sociaux*, 6:41–81, 1959.

[8] D. Hähnel. *Mapping with mobile robots*. PhD thesis, Universität Freiburg, 2005.

[9] C. Lattner. LLVM: An Infrastructure for Multi-Stage Optimization. Master's thesis, Computer Science Dept., University of Illinois at Urbana-Champaign, Urbana, IL, Dec 2002. *See* `http://llvm.cs.uiuc.edu`.

[10] F. Matsuno and S. Tadokoro. Rescue Robots and Systems in Japan. In *2004 IEEE International Conference on Robotics and Biomimetics*, pages 12–20. IEEE.

[11] Michael Doering, Stephan Rottmann, and Lars Wolf. Design and Implementation of a Low-Power Energy Management Module with Emergency Reserve for Solar Powered DTN-Nodes. In *Proceedings of the 3rd Extreme Conference of Communication (ExtremeCom 2011), Manaus, Brazil*, 2011.

[12] R. Nair, T. Ito, M. Tambe, and S. Marsella. Task Allocation in the RoboCup Rescue Simulation Domain: A Short Note. In A. Birk, S. Coradeschi, and S. Tadokoro, editors, *RoboCup 2001: Robot Soccer World Cup V*, volume 2377 of *Lecture Notes in Computer Science*. Springer Berlin Heidelberg, Berlin, Heidelberg, July 2002.

[13] I. Rekleitis, V. Lee-Shue, and H. Choset. Limited communication, multi-robot team based coverage. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, volume 4, pages 3462–3468 Vol.4. IEEE, 2004.

[14] P. Scerri, R. Vincent, and R. T. Mailler. *Coordination of Large-Scale Multiagent Systems*. Springer Publishing Company, Incorporated, Oct. 2010.

[15] S. Schildt, J. Morgenroth, W.-B. Pöttner, and L. Wolf. IBR-DTN: A lightweight, modular and highly portable Bundle Protocol implementation. *Electronic Communications of the EASST*, 37:1–11, Jan. 2011.

[16] P. Stone and M. Veloso. Task decomposition, dynamic role assignment, and low-bandwidth communication for real-time strategic teamwork. *Artificial Intelligence*, 110(2):241–273, June 1999.

[17] B. I. Triplett, D. J. Klein, and K. A. Morgansen. Cooperative Estimation for Coordinated Target Tracking in a Cluttered Environment. *Mobile Networks and Applications*, 14(3):336–349, Feb. 2009.

[18] Wolf-Bastian Pöttner, Felix Büsching, Georg von Zengen, and Lars Wolf. Data Elevators: Applying the Bundle Protocol in Delay Tolerant Wireless Sensor Networks. In *The Ninth IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2012)*, Las Vegas, Oct. 2012.