Ubiquitous Networking Robotics in Urban Settings[1]

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Abstract

In this paper we will present the objectives of a Network Robot System project denominated URUS, a European IST-STREP project of the FP6 program. The general objective of the project is the development of new ways of cooperation between network robots and human beings and/or the environment in urban areas. The focus of the project is in urban pedestrian areas, an important topic in Europe where there exists a growing interest in reducing the number of cars in the streets and improving the quality of life. In the paper we present the objectives and the goals to be achieved.

1. Introduction

European ancient cities are becoming difficult places to live due to noise, pollution, lack of quality facilities and security. Moreover, the average age of people living in large European cities is growing and in a short period of time there will be an important community of elderly people. City Halls are becoming conscious of this problem and are studying solutions, for example by reducing the areas of free circulation of cars. Free car areas imply a revolution in the planning of urban settings, for example, by imposing new means for transportation of goods to the stores, security issues, new ways of human assistance, etc. In this project we want to analyse and test the idea of incorporating a network of robots (which include robots, intelligent sensors, intelligent devices and communications) in order to improve quality of life in such urban areas.

Given the broad spectrum of an initiative like this, the URUS project will focus on designing and developing a network of robots that in a cooperative way interact with human beings and the environment for tasks of guidance and assistance, transportation of goods, and surveillance in urban areas. Specifically, our objective is to design and develop a cognitive networked robot architecture that integrates cooperating urban robots, intelligent sensors (video cameras, acoustic sensors, etc.), intelligent devices (PDA, mobile telephones, etc.) and communications. The main scientific and technological challenges that will be addressed in the project will be: navigation and motion coordination among robots; cooperative environment perception; cooperative map building and updating; task negotiation within cooperative systems; human robot interaction; and wireless communication strategies between users (mobile phones, PDAs), the environment (cameras, acoustic sensors, etc.), and the robots. Moreover, in order to facilitate the tasks in the urban environment and the human robot interaction, commercial platforms that have been specifically designed to navigate and assist humans in such urban settings will be given autonomous mobility capabilities, as well as a simple but friendly robot head.

Proof-of concept tests of the hardware and the software systems developed will take place in a pedestrian area of a city quarter of Barcelona.

The initiative of this project comes from the European Group inside of the Research Atelier on Network Robot Systems (NRS) (part of EURON) which is producing a Roadmap of Network Robots in Europe, one important company on communications and sensors, one SME company to augment the urban robot sensory capabilities to produce a versatile robot, and one company related to organizational studies for the city of Barcelona in conjunction with the Barcelona City Hall and the Government of Catalonia.

This Urban application has been selected to focus the principles of Network Robotics tackled in this project. However, the major contribution is scientific and technological, and in principle can be applied to any other ubiquitous robotic domain.

2. Objectives

The general objective of this project is the development of new ways of cooperation between network robots and human beings and/or the environment in urban areas, in order to achieve efficiently tasks that in the other way can be very complex, time consuming or too costly. For example, the cooperation between robots and video cameras can solve surveillance problems in urban areas, or the cooperation between robots and wireless communication devices can help people in several ways. The focus of the project is in urban pedestrian areas, an important topic in Europe where there exists a growing interest in reducing the number of cars in the streets and improving the quality of life. Network robots can be an important instrument to address these issues in the cities.

Network robots is a new concept that integrates robots, sensors, communications and mobile devices in a cooperative way, which means not only a physical interconnection between these elements, but also, for example, the development of novel intelligent methods of cooperation for task oriented purposes, new communication languages between the different elements, or new mobility methods using the ubiquity of sensors and robots. We have identified several scientific and technological challenges, when thinking on network robots for urban areas, which have been taken into account to define the objectives of this project.

The objectives of this project are the following:

1. A scientific and technological objective: Develop an adaptable cognitive network robot architecture which integrates the following functionalities (sub-objectives)
    a. Cooperative localisation and navigation.
    b. Cooperative environment perception.
    c. Cooperative map building and updating.
    d. Human robot interaction.
    e. Multi-task negotiation.
    f. Wireless communication with hand held devices, ubiquitous sensors, and other robots.

2. An experiment objective: Test the cognitive network robot architecture in two different urban tasks :
    a. Guiding and transportation of people and goods.
    b. Surveillance.

The **first main objective** of URUS is to develop an adaptable cognitive network robot architecture which integrates the basic functionalities required for the network robot system to do urban tasks.

- *Cooperative localization and navigation*: The **specific objective** is to extend the navigation capabilities of the robots by using cooperative localisation, perception, maps, short-term-planning robot navigation and cooperative control in unstructured and dynamic environments, in particular for urban settings.

- *Cooperative perception environment*: The **specific objective** here is to create and maintain a consistent view of the urban world containing dynamic objects, i.e., pedestrians, vehicles (autonomous or conventional small transportation vehicles), by means of the information provided by the robots and sensors embedded in the urban environment. Cooperative surveillance tasks including the fleet of robots and the embedded sensors will be addressed, including cooperative event detection and identification. The cooperation not only includes the fusion of data, but also the development of adequate actions for developing these tasks. Also, decentralized cooperative tracking techniques for the estimation of the people flow and other moving objects in a certain area will be considered.

- *Cooperative map building and updating*: The **specific objective** is to augment the classical static Simultaneous Localization and Map Building (SLAM) problem to deal with dynamic environments, and to be cooperative using not only a troupe of robots, but all the different elements of the NRS, where the static (background) and moving elements (foreground) must both to be taken into account, at all times during map construction. For urban areas, one could take advantage of a GIS (Geographic Information System) for background information and rely on state of the art cooperative SLAM for dynamically updating such map, and for detecting the foreground.

- *Human robot interaction:* The **specific objective** is developing a series of tools to have a robust communication interface between robots and persons and a simple but friendly head for the urban robots. A person will communicate to a robot by means of mobile phones, voice and gestures. The robot will communicate to a person by voice, a robot screen or through the mobile phone. The mobile phones will be the main communication interface that will allow the human beings to ask for assistance, help or any other order, and moreover they will be used to have the first location approximation of the person in the urban site. That means that we will define a bidirectional language communication using mobile phones. The robot touchscreen will be an interactive device to interchange information. The human gestures will be used for two actions: to express very simple commands and to locate a person in a specific urban point. An important issue will be to locate precisely a person by identifying its gestures. Finally, we will develop a simple but friendly head for the urban robots which will include the elements described in this work package.

- *Multi-task negotiation*: The **specific objective** is to use general optimal or suboptimal techniques to achieve multi-system task allocation among the members of the system, that is, the robots and the sensors and other systems of the environment. In this project, we will consider a set of heterogeneous robots with capabilities of interaction with the environment and with humans. The team of robots will be heterogeneous due to their motion capabilities (kinematic, dynamic), the type of sensors on-board, their visibility and the communication constraints between robots and the environment.

Figure 1: Guiding and transportation of people and goods

- *Wireless communication with hand held devices, ubiquitous sensors, and other robots*: The **specific objective** is to extend the localisation of human beings fusing information from typical communication systems (mobile phones, embedded and mobile sensors) and detecting hand human movements; improve the communication recovery with robots and humans; and establish a common wireless interactive language and protocol for the communication between humans (by means of mobile phone), robots and ubiquitous sensors.

The **second main objective** is to test this cognitive network robot architecture with the specific goal of achieving the deployment of a network of robots, sensors and communication devices for the following urban oriented tasks that will become experiments in the URUS project:

- Guidance and transportation of persons and goods.
- Surveillance.

The **first experiment** will consist in assisting people to find places to go and to transport people and goods from one place to another, using the best path taking into account for example, the map information and the on line street situation obtained by the network of robots. For the purpose of assisting people, some of the community of robots will have special interfaces to communicate with people (special monitor, new

generation of mobile phones, PDAs etc.) and the people will use similar devices to communicate with the network robots. In this task, we need an accurate estimate of the position of the person that requires the service, and for this reason sensor integration for localization is of uttermost importance; for example, by tracking the person with vision sensors, by aiding in his/her localization from mobile phone signals, by identifying the person by his/her movements and by referring such data to a map (if such exists). With respect to transportation, some of the robots will be prepared to transport people and goods (small size). Figure 1 shows a virtual view of the Guiding and Transportation of people and goods task.

The **second experiment** will consist in a surveillance task. Some robots in conjunction with the network will navigate the urban area to detect abnormal situations (vandalized urban furniture, big areas with trash, suspicious activity etc.). Moreover the network robots will be used to measure the flow of people in the streets or the flow of mobile elements in the area. For this purpose some of the community of robots will have special sensors and they will have to cooperate to exchange information, and give their location to send an alarm when they detect something strange.

In the two tasks, there will be cooperation among robots, sensors and communication systems. Basically the six functionalities aforementioned must be taken into account, however with different priorities.

The network of robots, sensors and communications will be tested in two different environments: a full experiment will be in the Campus of the Technical University of Catalonia, in Barcelona, which includes streets, passages, and closed environment (shops, restaurants, offices); and secondly a more limited testing will be performed in a selected "Superblock" (Supermanzana) of the city of Barcelona. At present there are several superblock studies in Barcelona, for example in Poblenue, 22@, and Gracia's quarter.

3. Partners

List of Participants

Partic. Role*	Participant name	Participant short name	Country
CO	Technical University of Catalonia (Institute of Robotics)	UPC	Spain
CR	Centre National de la Recherche Scientifique	LAAS	France
CR	Eidgenössische Technische Hochschule	ETHZ	Switzerland
CR	Asociación de Investigación y Cooperación Industrial de Andalucia	AICIA	Spain
CR	Scuola Superiore di Studi	SSSA	Italy

	Universitari e di Perfezionamento Sant'Anna		
CR	Universidad de Zaragoza	UniZar	Spain
CR	Instituto Superior Técnico	IST	Portugal
CR	University of Surrey	UniS	U.K.
CR	Urban Ecology Agency of Barcelona	UbEc	Spain
CR	Telefónica I+D	TID	Spain
CR	RoboTech	RT	Italy

*CO = Coordinator
 CR = Contractor

4. Work Plan

In order to accomplish the aforementioned objectives, we have structured the project in the following levels (see Figure 2):

Specification level: In this level we will identify the basic operational requirements for each one of the two experimental situations proposed, the needed hardware, software and communications, and detailed software modules that will be develop in the URUS project. Moreover, we will study the required urban regulations and procedures from the point of view of mobility, deployment of devices, communications, security and monitoring. Thus, the first type of specification is oriented to the technological requirements of the project; whereas the second type is oriented to setting general conditions for the future deployment of network robots in urban settings.

Technologies level: At this level lays the scientific core of the project. It will consist of the development of innovative techniques for networked robots, which will be based on the latest research and development taking place at the university and company research centres from the consortia. This level consists on six work packages, each one developing a specific scientific and technological issue regarding network robotics. The outcome of each one of these work packages will be a set of independent modules that will serve specific functionality within the URUS project. These work packages include localization and navigation, environment perception, map building, human robot interaction, multitask allocation, and networking.

Experimentation level: In this third level, the objective is to set up two experimental settings to show how the networked robots can help humans in urban areas. One work package will be devoted to each of the settings, namely, guiding and transportation, and surveillance. The work packages include system integration of the modules developed within the technological level of the project, as well as experiments, using a distributed set of sensors and robots.

The project will use an estimated set of 10 mobile robotics platforms, coming from the different partners. We will use existing platforms already developed by the partners and we will only include the appropriate sensors needed to extend their capabilities to deal

with the challenges posed by cooperative multirobot tasks in urban settings. In addition, in order to obtain a friendly human robot interaction, one of the companies will develop an intelligent robot head for the future urban robots, which will be tested in the experiments. Moreover, the communication companies participating in the project will develop and serve specific needs and techniques to best interconnect our robot network.

Figure 2: Graphical representation of the WP and their interdependencies

5. Conclusions

The URUS is an ambitious project that tries to investigate on the key issues of Network Robot Systems on Urban Sites and make some experiments to verify the scientific and experimental results developed in the project. URUS is a 3 year project that will start on December 2006 and will finish on November 2009.

6. References

[1]   Akyildiz, I.F., and Kasimoglu, I.H.: "Wireless sensor and actor networks: research challenges", *Ad Hoc Networks*. 2 (4), pp. 351-367, 2004.

[2] Alami, R. "A Multi-Robot Cooperation Scheme Based on Incremental Plan-Merging" In Proc. R. Hirzinger and G. Giralt, eds., Robotics Research: The Seventh International Symposium, Springer Verlag, 1996.

[3] Alami, R., "On Architectural and Decisional Issues for Multi-Robot Cooperation" in Multi-Robot Systems: From Swarms to Intelligent Automata, Volume II, Proc. International Workshop on Multi-Robot Systems, Schultz, Alan C.; Parker, Lynne E.; Schneider, Frank E. (Eds.) 2003.

[4] Alami, R., Chatila, R., Fleury, S., Ghallab, M., Ingrand, F., "An architecture for autonomy" *International Journal of Robotic Research*, 17(4), pp.315-337, April 1998.

[5] Alami, R., Clodic, A., Montreuil, V., Sisbot, E.A., Chatila, R. "Toward Human-Aware Robot Task Planning", Proc. AAAI Spring Symposium, Stanford, USA, March 2006.

[6] Alami, R., Fleury, S., Herrb, M., Ingrand, F., Robert, F. "Multi robot cooperation in the Martha project", *IEEE Robotics and Automation Magazine*, 5(1), pp. 36-47, March 1998.

[7] Alami, R., Ingrand, F., Qutub, S. "A scheme for coordinating multi-robot planning activities and plans execution", Proc. 13th European Conference on Artificial Intelligence, Brighton, August 1998, pp.617-621.

[8] Alami, R., Robert, F., Ingrand, F., Suzuki, S. "Multi-robot Cooperation through Incremental Plan-Merging", Proc. IEEE International Conference on Intelligent Robots and Systems, Nagoya, May 1995.

[9] Alami, R., Silva da Costa Botelho, S. "Plan-based multi-robot cooperation" Advances in Plan-Based Control of Robotic Agents. *Lecture Notes in Artificial Intelligence* 2466, Springer, 2002.

[10] Albekord K., A. Watkins, G. Wiens, N. Fitz-Coy "Multiple-Agent Surveillance Mission with Non-Stationary Obstacles", Proc. Florida Conf. on Recent Advances in Robotics, Univ. Central Florida May 6-7, 2004.

[11] Andrade-Cetto, J. and Sanfeliu, A. "The effects of partial observability when building fully correlated maps". *IEEE Transactions on Robotics*, 21(4):771-777, August 2005.

[12] Andrade-Cetto, J. and Sanfeliu, A. *Environment Learning for Indoor Mobile Robots. A Stochastic State Estimation Approach to Simultaneous Localization and Map Building*, volume 23 of *Springer Tracts in Advanced Robotics*. Springer, 2006.

[13] Andrade-Cetto, J., Vidal-Calleja, T., and Sanfeliu, A. "Multirobot C-SLAM: Simultaneous localization, control, and mapping". Proc. IEEE ICRA05 Workshop on Network Robot Systems, Barcelona, April 2005.

[14] Belta, C., and Kumar, V. Abstraction and control for groups of robots. *IEEE Transactions on Robotics*, 20(5), 2004.

[15] Botelho, S., Alami, R. "A multi-robot cooperative task achievement system", Proc. IEEE International Conference on Robotics and Automation, San Francisco, April 2000, Vol.3, pp.2716-2721.

[16] Botelho, S., Alami, R. "M+: a scheme for multi-robot cooperation through negotiated task allocation and achievement", Proc. IEEE International Conference on Robotics and Automation, Detroit, May 1999, pp.1234-1239.

[17] Bothelo, S., Alami, R., "Robots that cooperatively enhance their plans", DARS 2000, October 4-6, 2000, Knoxville, Tennessee, USA

[18] Breazeal, C. *Designing Sociable Robots,* The MIT Press, 2002.

[19] Cai, Q. and Aggarwal, J.K. "Tracking human motion in structured environments using a distributed-camera system". *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 21(12):1241–1247, November 1999

[20] Chaimowicz, L. Campos, M. F. M. Kumar, V. Dynamic Role Assignment for Cooperative Robots, Proc. IEEE Int. Conference on Robotics and Automation, pp. 293-298, 2002.

[21] Chlamtac, I., Conti, M., and Liu, J.. "Mobile ad hoc networking: imperatives and challenges". *Ad Hoc Networks*. 1 (1), pp.13-64, 2003.

[22] Clodic, A., Fleury, S., Alami, R., Herrb, M., Chatila, R., "Supervision and Interaction: Analysis from an Autonomous Tour-guide Robot Deployment," Proc. International Conference on Advanced Robotics, 2005.

[23] Dietl, M., Gutmann, J.-S., and Nebel, B. "Cooperative Sensing in Dynamic Environments", Proc. International Conference on Intelligent Robots and Systems, 2001.

[24] Dissanayake, M.W.M.G., Newman, P., Clark, S., Durrant-Whyte, H.F., and Csorba, M. "A solution to the simultaneous localization and map building problem", *IEEE Transactions on. Robotics and Automation*, vol. 17, no. 3, pp. 229-241, Jun. 2001.

[25] Fischer, K. Mueller, J. P. Pischel, M. Cooperative Transportation Scheduling: An Application Domain For DAI , *Applied Artificial Intelligence* 10(1):1-34, 1996.

[26] Fox, D., Burgard, W., Kruppa, H., and Thrun, S. "A Probabilistic Approach to collaborative Multi-Robot Localization", *Autonomous Robots* 8, 325-344, 2000.

[27] Frese, U. A Discussion of Simultaneous Localization and Mapping. In *Autonomous Robots*, 20 (1), pp. 25–42. 2006.

[28] Gerkey, B. P., Mataric, M. J.: "A formal analysis and taxonomy of task allocation in multi-robot systems". *International Journal of Robotic Research*, 23(9):939-954, September 2004.

[29] Gerkey, B. P., Mataric, M. J.: "Multi-robot task allocation: analyzing the complexity and optimality of key architectures" Proc. IEEE Int. Conference on Robotics and Automation, pp. 3862-3868, 2003.

[30] Gerkey, B. P., Mataric, M. J.: "*On Multi-Robot Task Allocation*", PhD thesis, University of Southern California, 2003

[31] Goradia A., Xi, N., Cen, Z., and Mutka, M. "Modeling and Design of Mobile Surveillance Networks Using a Mutational Analysis Approach", Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, California, USA, 2005.

[32] Gravot F., Cambon, S., and Alami, R. "Asymov: a planner that deals with intricate symbolic and geometric problem", Robotics Research, Proc. The Eleventh International Symposium Series: Springer Tracts in Advanced Robotics, Vol. 15 Dario, Chatila (Eds.) 2005, XVI, 595 p.,

[33] Hara, M. Fukuda, M. Nishibayashi, H. Aiyama, Y. Ota, J. Arai, T. Motion control of cooperative transportation system by quadruped robots based on vibration model in walking, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol 3, pp. 1651-1656, 1999.

[34] Howard, A., Mataric, M. J. and Sukhatme, G. "Putting the 'i' in 'team': an ego-centric approach to cooperative localization," in Proc. IEEE International Conference on Robotics and Automation, Taipei, Taiwan, Sep. 14-19 2003, pp. 868–874.

[35] Hyams, J., Powell, M.W., and Murphy, R. "Cooperative Navigation of Micro-Rovers Using Color Segmentation", *Autonomous Robots*, Vol 9; part 1, pages 7-1, 2000.

[36] Jennings, C., Murray, D., and Little J.J., "Cooperative Robot Localization with Vision-Based Mapping ", Proc. IEEE International Conference on Robotics and Automation, 1999.

[37] Jung, I-K, and Lacroix, S. "High resolution terrain mapping using low altitude aerial stereo imagery", in International Conference on Computer Vision, Nice (France), 2003.

[38] Konolige, K., Gutmann, J.-S., Guzzoni, D., Ficklin, R., and Nicewarner K. "A mobile robot sense net". Proc. SPIE 3839 Sensor Fusion and Decentralized Control in Robotic Systems II, Boston, Sept. 1999.

[39] Krishna, K.M., Alami, R., Siméon, T. "Safe proactive plans and their execution", Robotics and Autonomous Systems, 54, 244-255, 2006.

[40] Lemaire, T., Alami, R., Lacroix, S. "A distributed tasks allocation scheme in multi-UAV context", Proc. International Conference on Robotics and Automation, New Orleans, 2004, 6p.

[41] Lemaire, T., Lacroix, S., and Sola, J. "A practical bearing-only SLAM algorithm", in IEEE International Conference on Intelligent Robots and Systems, Edmonton, 2005

[42] Martinelli, A., Pont, F. and Siegwart, R. "Multi-Robot Localization Using Relative Observations". Proc. IEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005.

[43] Mehrabian, A. "Communication without words," in *Psychology Today*, vol. 2, 1968, pp. 53-56.

[44] Merino, L., Caballero, F., Martínez-de Dios, J.R., Ferruz, J. and Ollero, A. "A cooperative perception system for multiple UAVs: Application to automatic detection of forest fires". *Journal of Field Robotics*. John Wiley. 2006. in Press.

[45] Milella A., Pont, F. and Siegwart, R. "Model-Based Relative Localization for Cooperative Robots Using Stereo Vision". Proc. Twelfth annual Conference on Mechatronics and Machine Vision in Practice, 2005.

[46] Montemerlo, M., S. Thrun, D. Koller, B. Wegbreit. "FastSLAM: a factored solution to simultaneous mapping and localization problem". Proc. 18th Natl. Conf. on Artificial Intelligence, pp. 593-598, 2002.

[47] Montesano L., Gaspar J., Santos-Victor J., Montano L.: "Cooperative localization by fusing vision-based bearing measurements and motion". Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, Alberta, Canada, Agosto 2-6, 2005, 1445-1450, 2005.

[48] Montesano L., Montano L., Burgard W.: "Relative Localization for Pairs of Robots Based on Unidentifiable Moving Features". Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems. Sendai, Japan, Sept 28-Oct. 2, pp. 1537-1543, 2004.

[49] Moreno, F., Andrade-Cetto, J., and Sanfeliu, A. Fusion of color and shape for object tracking under varying illumination. In F. J. Perales, A. J. C. Campilho, N. P. de la Blanca, and A. Sanfeliu, editors, Proc. 1st Iberian Conference on Pattern Recognition and Image Analysis, volume 2652 of *Lecture Notes in Computer Science*, pages 580-588, Puerto de Andratx, June 2003. Springer-Verlag.

[50] Parker, "Alliance: An architecture for fault-tolerant multi-robot cooperation", *IEEE Transactions on Robotics and Automation* 14(2), 220-240, 1998.

[51] Pynadath, D. V., Tambe, M : "The communicative multiagent team decision problem: Analyzing teamwork theories and models", *Journal of Intelligence Research* 16, 389-423, 2002.

[52] Raven, P. et al., "RASANT: Radio Aided Satellite Navigation Technique", EBU Technical Review No. 267, Spring 1996.

[53] Ribeiro P. and Santos-Victor, J.. "Human Activity Recognition from Video: modeling, feature selection and classification architecture". Proc. BMVC Workshop on Human Activity and Modelling, Oxford, UK, September 2005.

[54] Richards, A., and How, J. P. Robust Model Predictive Control with Imperfect Information Proc. IEEE American Control Conference, June 2005, pp. 268-274.

[55] Roumeliotis, S.I., and G.A. Bekey, G.A., "Distributed Multi-Robot Localization", *IEEE Transactions on Robotics and Automation,* 18(5), pp. 781-795, Oct. 2002.

[56] Roumeliotis, S.I., and I.M. Rekleitis, I.M., "Propagation of Uncertainty in Cooperative Multirobot Localization: Analysis and Experimental Results", *Autonomous Robots,* 17(1), pp. 41-54, July 2004.

[57] Rybski E., Hougen, D. F., Stoeter, S. A., Gini, M., and Papanikolopoulos, N. "Control of Multiple Small Surveillance Robots at AAAI 2000", Proc. AAAI 2000 Mobile Robot Competition and Exhibition Workshop, August 2000.

[58] Sanfeliu, A., Alquézar, R., Andrade, J., Climent, J., Serratosa, F., and Vergés, J. Graph-based representations and techniques for image processing and image analysis. *Pattern Recognition*, 35:639-650, March 2002.

[59] Saptharishi M., Oliver, C. S., Diehl, C., Bhat, K., Dolan, J., Trebi-Ollenu, A., and Khosla, P. "Distributed Surveillance and Reconnaissance using Multiple Autonomous ATVs: CyberScout", *IEEE Transactions on Robotics and Automation* 18(5):826-836, October 2002.

[60] Schmitt, T., Hanek, R., Buck, S., and Beetz, M. "Cooperative probabilistic state estimation for vision-based autonomous mobile robots", *IEEE Transactions on Robotics and Automation* 18(5), October 2002

[61] Schulz, S., Burgard, W., Fox, D., and Cremers, A.B. "People Tracking with a Mobile Robot Using Sample-based Joint Probabilistic Data Association Filters". *International Journal of Robotics Research*, 2003.

[62] Shin, J., Lee N., Thrun S., and Guibas, L.J. "Lazy inference on object identities in wireless sensor networks", Proc. Fourth International Symposium on Information Processing in Sensor Networks, pp. 174-180.

[63] Siméon, T., Cortés, J., Laumond, JP., Sahbani, A. "Manipulation planning with probabilistic roadmaps". *The International Journal of Robotics Research*, 23(7-8), 2004.

[64] Smith, R.C. and Cheesemann, P. "On the representation and estimation of spatial uncertainty", *International Journal of Robotics Research*, 5(4), pp. 56-68, 1986.

[65] Stentz, A. T., Dias, M.B. "A free market architecture for coordinating multiple robots", Technical Report CMU-RI-TR-99-42, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, 1999.

[66] Suda, R., Kosuge, K., Kakuya, H. "Object-Impedance-Based Cooperative Handling of Object by Mobile Robot Helper and Human Using Visual and Force Information", Proc IEEE/ASME International Conference on Advanced Intelligent Mechanics, pp.592-597, 2003.

[67] Taylor C., Rahimi, A., Bachrach, J., and Shrobe H. "Simultaneous Localization and Tracking in an ad Hoc Sensor Network", Proc. Information Processing in Sensor Networks, 2006.

[68] Vidal-Calleja, T., Davison, A.D., Andrade-Cetto, J., and Murray, D.W. "Active control for single camera SLAM". Proc. IEEE International Conference on Robotics and Automation, Orlando, May 2006. To appear.

[69] Zecca, M., Roccella, S., Carrozza, M.C., Miwa, H., Itoh, K., Cappiello, G., Cabibihan, J-J., Matsumoto, M., Takanobu, H., Dario, P., Takanishi, A. "On the development of the Emotion Expression Humanoid Robot WE-4RII with RCH-1", Proc IEEE-RAS International Conference on Humanoid Robots (Humanoids2004), Vol.1, pp.235-252, 2004.

[70] Zollo, L., Siciliano, B., Laschi, C., Teti, G., Dario, P. "An Experimental Study on Compliance Control for a Redundant Personal Robot Arm", *Robotics and Autonomous Systems*, Vol.44, Issue 2, pp.101–129, 2003.