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An integrated testbed for heterogeneous mobile robots and other cooperating objects

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Abstract—**This paper describes a testbed for general experimentation involving Cooperating Objects (COs). Its architecture considers all COs at the same level. It allows a multiple schemes including multi-robot, WSNs experiments and robot-WSN collaboration working as peers. Currently comprised of 6 mobile robots (5 Pioneer 3AT and one outdoor robot) and 40 static WSN nodes equipped with cameras (IEEE1394 for the robots and embedded cameras for the WSN nodes), laser rangers, and other sensors, it can be easily extended with other hardware due to the use of a modular architecture and standard software tools and interfaces. The testbed allows testing centralized and distributed techniques, is suitable for indoors and outdoors and can be accessed through the Internet for online remote monitoring and visualization. The main experiments already carried out, some of which are described in the paper, focused on cooperative perception and robot-WSN collaboration for network repairing.**

I. Introduction

In the last years different technological fields have emerged in the broad context of embedded systems. Disciplines such as pervasive and ubiquitous computing, where objects of everyday use are endowed with computational, sensing and communication facilities, have appeared. Furthermore, nodes in Wireless Sensor Networks (WSN) collaborate together using ad-hoc network technologies to achieve a mission of supervision of some area or some particular process [1]. The high complementarities and synergies among these technologies have facilitated their convergence in what has been called Cooperating Objects.

As stated in [2], Cooperating Objects (COs) consist of embedded computing devices equipped with communication and sensing or actuation capabilities that are able to cooperate and organize themselves autonomously into networks to achieve a common task. Important notions such as heterogeneity, wireless communication, dynamics/ad-hoc nature, and cost are present to various degrees in these systems.

The cooperation of diverse types of COs enhances their individual performance, providing new features and a wide variety of possibilities. In fact, cooperation between WSN and mobile robots has attracted significant research efforts in the recent years. Mobile robots using its onboard sensors can improve the sensing capabilities of a static WSN. Besides, robots mobility and their capability to carry equipment are useful to enlarge the communication ranges of static WSN nodes. Mobile robots have been proposed for WSN deployment [3], repairing [4], WSN data retrieving [5] and WSN localization [6], among others.

One of the main difficulties in the research on COs is the lack of suitable tools for testing and validating algorithms, techniques and applications that combine the three disciplines, [2]. In this sense, although a number of testbeds for mobile robots, [7] [8] [9], and for WSN [10] [11] [12] have been developed, they cannot be easily extended to integrate other types of COs. Few CO testbeds with robots and WSNs have been developed and they are focused on specific aspects. The Clarity UbiRobot testbed [13] has a balanced approach whereas Mobile Emulab [14] is mainly focused on WSN experiments, providing a testing platform for WSN mobile nodes. Explorebots [15] concentrates on the robotics approach. ISROBOTNET [16] was designed as a response to the necessities of a concrete application within the framework of a project. In fact, the lack of suitable CO testbeds has been considered of an important drawback for the development of the CO research [2].

The paper describes an integrated testbed for mobile robots, static and mobile wireless sensor nodes and other cooperating objects. It is being developed in the EU-funded Cooperating Object Network of Excellence CONET (INFSO-ICT-224053) to serve CO academic and industrial communities. It allows equanimity among heterogeneous COs so that they can have the same weight in an experiment, working as peers. Its open and modular architecture employs standard software tools and interfaces making the addition of new elements fairly easy or straightforward. Furthermore, it supports outdoor experiments and allows online remote experiment monitoring. To the best of our knowledge there are not other testbeds for heterogeneous objects with the above mentioned characteristics.

The structure of this paper is as follows. Section II briefly describes the elements currently involved in the testbed and its infrastructure. The software architecture is presented in Section III. Section IV illustrates the testbed possibilities with some experiments that have been already carried out. Conclusions and acknowledgments are the final sections.

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II. THE CONET INTEGRATED TESTBED

Fig. 1 shows a general scheme of a typical deployment of the described testbed. The testbed is set in a room of more than 400 m^2 (20 m x 20 m) crossed longitudinally by a line of 3 columns. Two doors (see left in Fig. 1) lead to a symmetrical room if an extension of the testbed is required.

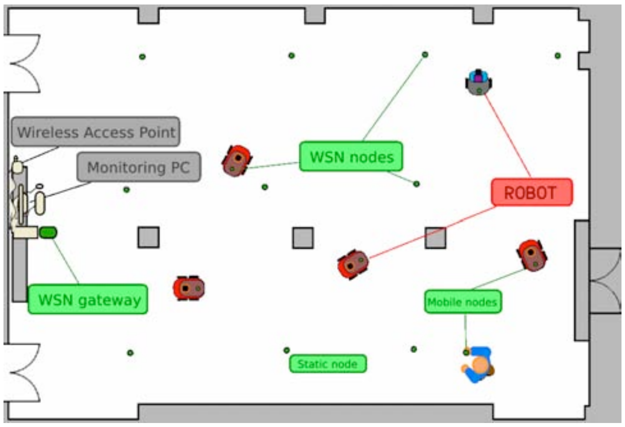

Fig. 1. General scheme of the integrated testbed.

Currently, the testbed is comprised mainly of autonomous robotic systems and a WSN with static and mobile nodes. This includes 5 skid-steer holonomic *Pioneer 3-AT* platforms manufactured by *MobileRobots©*. The basic robotic platforms are enhanced with an extra Advantech PCM-3372 PC-104 embedded PC, a Wireless a/b/g/n Bridge and several sensors including a *Hokuyo UTM-30LX* 2D laser with a range of 30 m and 0.25 degrees of resolution at 25 ms/scan, and one *IEEE1394* color camera, see, Fig. 2. Besides, a WSN node is connected by RS232 to each robot, being the robots also part of the WSN network.

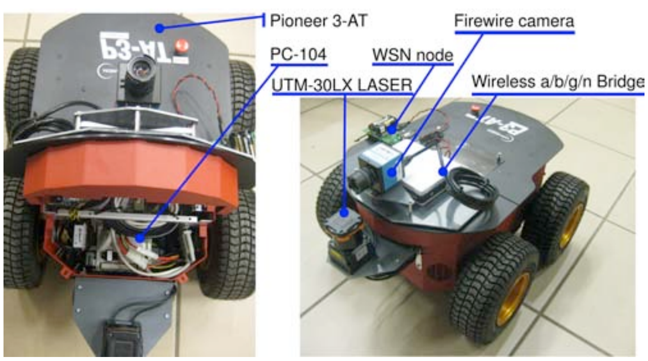

Fig. 2. One of the testbed robots and its onboard sensors.

The testbed WSN comprises of static and mobile *Xbow* nodes, including those mounted on the robotic platforms. The nodes can be equipped with *Xbow MTS400* or *MTS300* sensor boards, see Fig. 3 left, with accelerometers and sensors to measure temperature, humidity, pressure and light intensity, among others, [17]. The WSN nodes have been integrated with smoke detectors, CO, CO_2 and H_2 sensors, [18]. Also, they can be equipped with embedded cameras such as *CMUCAM2* and *CMUCAM3*, [19], see Fig. 3 right.

Note that there exists a double wireless network among the elements currently involved: the WSN itself and the wireless LAN linking all the robots. Fig. 4 shows the physical connections among the testbed elements.

Fig. 3. Left) *Xbow Mica2* node with *MTS400* and *MTS300* sensor boards. Right) Set of five CMUCAM3 and three CMUCAM2.

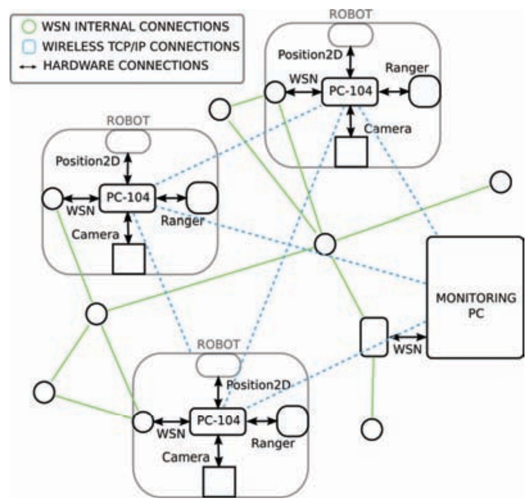

Fig. 4. Physical connections among the testbed elements

All this hardware is all-terrain and therefore suitable for outdoors. The Ackerman configuration robot in Fig. 5 also participates in outdoor experiments. Based on a gas RC model, it has been enhanced with a PC-104, a Hokuyo 2D Laser and an IEEE1349 camera and has been endowed with simple control and navigation functions.

As shown in Section III the testbed modular software architecture supports straightforward, or easy, incorporation of other robotic platforms, sensors or WSNs.

The testbed infrastructure also includes IP cameras to provide general views of the experiment and a Monitoring PC, which has access to all testbed elements, and runs experiment visualization, monitoring and data logging tools. It also allows interaction through the Internet, i.e. remote experiment allocation and online execution, visualization, monitoring and logging using its website [20] and a Virtual Private Network (VPN).

Outdoors robot localization and orientation is carried out with GPS and an IMU. A beacon-based computer vision system to measure the robots ground truth location and orientation is used as part of the testbed indoors architecture. Each robot is equipped with a calibrated webcam pointing at the room ceiling, on which beacons have been stuck. Similar approaches consisting of cameras installed on the room ceiling, such as mezzanine, [21], require a significant number of cameras, and processing power to analyze the images to cover a large scenario such as ours.

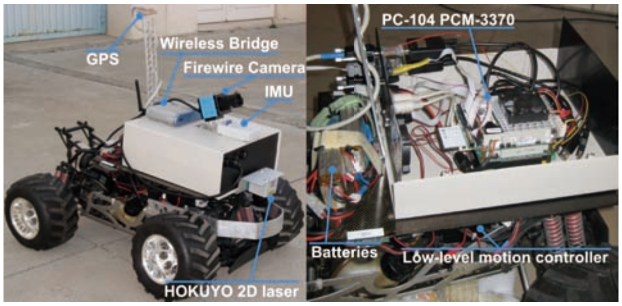

Fig. 5. Testbed outdoors robot and its onboard sensors.

In this case each robot applies locally beacon detection algorithms and determines its pose using homography-based techniques. The beacons are distributed in a uniform square grid on the room ceiling, in such a way that, from any robot pose, the webcam (with wide FOV lenses) sees in the image at least one beacon square, i.e. an imaginary square with one beacon at each corner.

Fig. 6 summarizes the steps of the method. The first step is to apply efficient thresholding algorithms to identify black beacons in a white background (ceiling) and extract geometrical features from the segmented beacons for classification. In order to consider robot orientation, the beacons are designed so that classification is achieved using rotation-robust and efficient features, e.g. object aspect ratio and area corrected taking into account the distance from each pixel to the image center. Lens distortions are corrected assuming simple radial models.

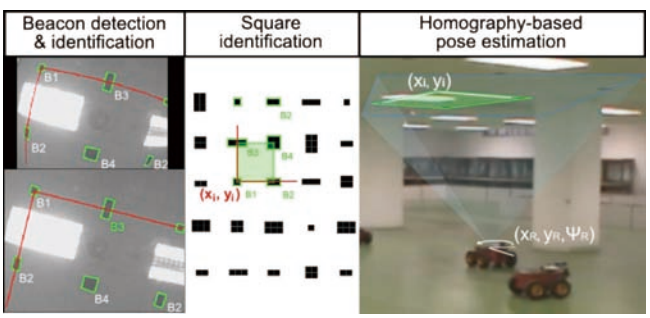

Fig. 6. Left) Beacon detection and identification. Center) Square identification. Right) Homography based robot pose estimation.

The next step is to identify the beacon square present in the image. The beacon grid is a concatenation of beacon squares. The beacon squares are designed in a way that any beacon square in the room is singular even considering rotations. Thus, analyzing the beacon types that form the square in the image it is simple to determine univocally the location of the beacon square in the image. The last step is to apply homography-based techniques to determine the robot location and orientation on the plane, assuming that the locations of the centers of the beacons in the identified beacon square are known. Experimental tests, in which the beacons locations were not measured with special care, showed a localization error with an average of less than 8 mm. and standard deviation of less than 4 mm. The method is computationally efficient and it can be executed at a suitable frame rate in the robot embedded PCs, where other processes, such as the robot user programs being tested, are also running.

As described, the testbed provides infrastructure for a wide range of experiments, being flexible in the configuration and location of the scenario. As shown in the next section, its software architecture supports the experimentation of centralized and distributed techniques as well.

III. Software Architecture

Openness and flexibility are main requirements in the design of the testbed. It should allow interaction of heterogeneous COs with wide differences in sensing, computing and communication capabilities. On the other hand, it should support user programs for a wide range of experiments. The solution adopted is to use an integrating layer through which all the modules intercommunicate using standardized interfaces.

The testbed uses Player as the main hardware abstraction layer, Fig. 7. Player is an open-source network server for robot control that includes support for a large variety of devices, robots and sensors [22] [23], facilitating their integration in the testbed. This hardware abstraction layer communicates, on one side, robots, sensors and WSN and, on the other side, programs for experimentation developed by testbed users and also the monitoring and logging tools provided by the testbed infrastructure. Thus, Player facilitates not only integration of COs but also the testbed user programming process.

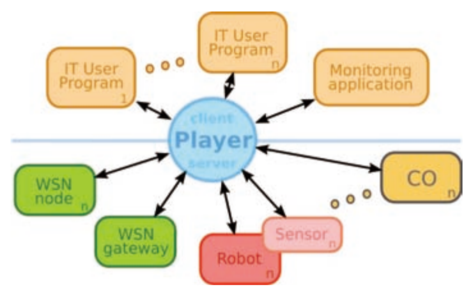

Fig. 7. Basic testbed software scheme for interoperability among COs.

An interface between WSN nodes and Player has been designed so that the internal behavior of the WSN including its message format, protocols, programming language and WSN operating system are transparent to the rest of the testbed COs. The same interface is used for communication with individual WSN nodes (e.g. robot with its connected node) and the overall WSN (e.g. robot or monitoring PC with the WSN gateway). This interface comprises of bidirectional messages consisting of a header with routing information and a body, which depends on its type. General **data** messages, **requests** and **commands** are considered for the incoming and outgoing messages. Some application-dependant message types such as *Radio Signal Strength Indicator* (**RSSI**), **sensor** data and **alarm** were defined as well. Any WSN complying with this interface can be straightforwardly integrated in the testbed. It was necessary to specifically develop a new Player driver for

Xbow WSN motes and redesign the corresponding Player interface to ensure compatibility with a wide range of WSN models.

Fig. 8 shows a basic diagram of the software architecture. This scheme allows centralized as well as fully distributed approaches. The testbed architecture also includes services to facilitate experiment development. Mobile robots are provided with services for random motion with obstacle avoidance, robot localization using laser and odometry and local and global navigation. WSN network formation and data gathering and collection services are also available.

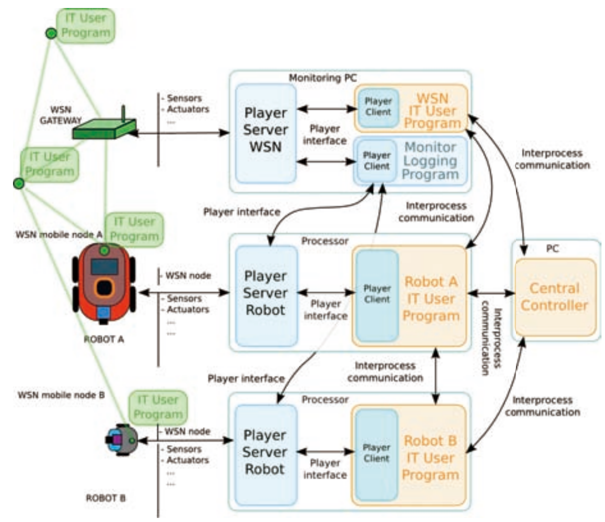

Fig. 8. General scheme of the testbed software architecture.

IV. EXPERIMENTS

The testbed can cope with a wide variety of experiments involving cooperation among uniform or heterogeneous COs. It can be used in experiments focused on multi-robot schemes (e.g. multi-robot task allocation), on WSNs (e.g. evaluation influence of motion in WSN link quality) and also on robot-WSN collaboration. To illustrate its capabilities we describe some experiments on cooperative perception and robot-WSN cooperation for network repairing that have been carried out in the testbed.

A. Cooperative perception

The static and mobile COs employed in the testbed are endowed with cameras. Each robot is equipped with a firewire camera and has capabilities to locally process the images. Also, WSN static nodes are equipped with embedded CMUCAM2 and CMUCAM3 cameras. However, WSNs do not have bandwidth required for transmission of images at suitable frame rates. Thus, the images are analyzed locally at each WSN node and only the processed, and low-bandwidth, results are sent through out the WSN.

In a simple experiment the objective is to detect, locate and track moving objects using static WSN cameras. In these experiments one or more robots are used as targets. Validation and comparison of different techniques is possible using the ground truth pose of the robots as described in Section II. Segmentation methods are applied locally at each embedded camera. Only the location of the objects segmented on the image plane is sent through the WSN. In a centralized version, the results from the nodes are transmitted to a common element for its processing. Assuming that the cameras are internally calibrated and their location and orientation are known, the measures are processed by data fusion techniques such as centralized Bayesian filters.

For instance, executing the data fusion method in the PC linked to the WSN gateway requires transmitting the data through out the network, which involves retransmissions, delays, energy and WSN bandwidth consumption. In a different approach the nodes with measures of the same target are grouped in “clusters”. If the data fusion method is executed in a cluster node designated as leader, the data flow is kept within the cluster. However, WSN can be prone to communication failures. Robustness can be obtained adopting a decentralized scheme in which each cluster node maintains their perception by integrating its own measurements with those received from the rest of the cluster nodes.

Some of these techniques have been experimented in the described testbed, see Fig. 9 right. Object tracking techniques for WSN embedded cameras using different centralized data fusion methods such as Maximum Likelihood and efficient Extended Kalman Filters are described in [24]. Fig. 9 left shows the results of tracking with three cameras and the ground truth.

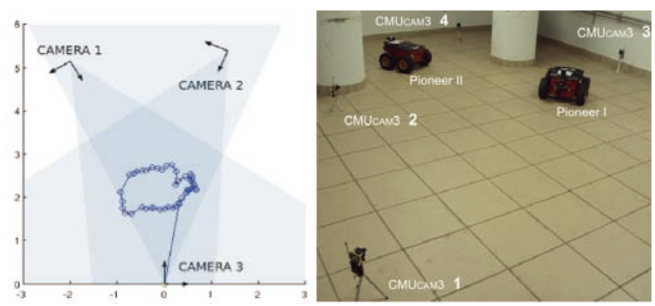

Fig. 9: Left) Result of multi-camera object tracking using an Extended Kalman Filter. Right) Picture taken during an experiment with two target robots and four CMUCAM3 cameras.

All static and mobile nodes used in the testbed can obtain RSSI measurements. Different perception approaches can be experimented using RSSI as main sensors. In indoor scenarios RSSI contains significant noise mainly attributed to reflections, see Fig. 10 left. The greater part of the experiments has been performed outdoors to avoid reflections. In a simple case the objective is to detect, locate and track one or more targets that emit beacon messages by using the RSSI readings gathered by fixed nodes at known locations, see Fig. 10 right. In a centralized version, the information from the cluster nodes is sent to a common entity, in which an Extended Information Filter method has been used to locate and track the object [25].

Cooperative perception experiments combining RSSI, cameras and robot laser readings can led to assessment of which sensor is more informative for target localization and tracking. These analyses are object of current research.

In the previous schemes all the sensors are in use regardless of the cost in terms of computing, communications or energy consumption. An active perception approach is to select sensors by dynamically optimizing the information gain they provide versus the cost of the information. In the field of COs, the active perception problem can be defined as the procedure to determine the best actions that should be performed by the COs from the point of view of information gathering. In general, active perception can mean selecting sensory actions, for instance activating a particular sensor of the network or switching on one embedded camera. Under a cooperative active perception approach robots can take actions, such as given two routes to get to a desired location, take the more informative one, in order to improve not only their own but also the overall perception.

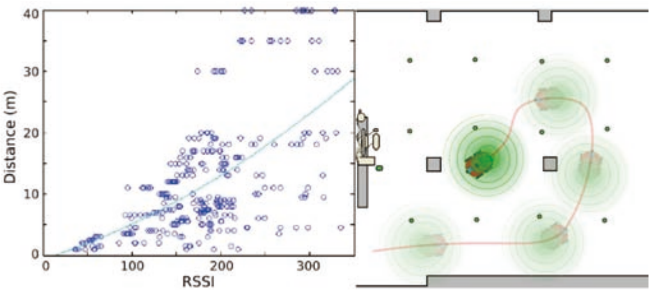

Fig. 10. Left) RSSI-Distance relationship in an open scenario. Right) Basic scheme of the experiment.

In most strategies, the selection of the actions involves information gain VS cost analyses. In the so-called greedy algorithms the objective is to decide which is the next best action to be carried out, without taking into account long-term goals. POMDPs [26], on the other hand, consider the long-term goals providing an elegant way to model the interaction of a CO in an environment, both of them uncertain. Also, POMDPs can tackle more elaborate scenarios, in which it is possible to prioritize the tracking of certain targets or to explicitly reason about communicating with other sensors. For instance, a fixed node could ask a mobile node to examine a certain location.

The testbed is a suitable tool for experimenting cooperative active perception techniques allowing the possibility of centralized as well as decentralized approaches and is currently being used for research involving WSN CMUCAM3 and robot cameras for active target tracking.

B. Robot-WSN collaboration for network repairing

Robustness is crucial for the performance of COs. Mobile nodes can be used to maintain and recover network connectivity. Robots are also useful for the deployment of the network using criteria based on connectivity fault tolerance and sensor optimal coverage. Once the network has been deployed, the first step is to apply network diagnosis e.g. determining radio connectivity boundaries and holes or identifying malfunctioning WSN nodes. Mobile nodes can be used to detect/confirm radio connectivity holes predicted by radio model analyses. Once faults have been detected, the robots can be used for WSN repairing and healing applying several strategies.

Relocation of nodes is useful when the damage of the net does not compromise the whole mission, for instance in case of incorrect or non-optimal location of deployed nodes. When the damages severely compromise the mission an option is to replace nodes. Robots mobility and their capability to carry pieces of equipment are useful for node relocating and replacing. In [27] ground robots are used to deploy nodes making use of the information gathered to determine the next deployment location. In the AWARE project we have experimented node deployment with aerial robots with higher maneuverability at low accessible locations, [3].

In the testbed we have performed network repairing experiments in which, once the main radio connectivity boundaries have been identified, the robots are assigned with tasks to move to the WSN healing location, acting as communication rely nodes, see Fig. 11. Network formation and radio propagation models were used to identify suitable healing locations. A video of the experiment implemented indoors can be visualized at [28]: the nodes power was reduced to simulate connectivity problems.


Fig. 11. Network repair experiment in the testbed indoor scenario.

When there are very high damages in the network an option is to collect the data using the robots following a "data mule" approach, [3]. These schemes are particularly useful in very large scenarios or with sparse-deployed WSNs. The robot is commanded to move close to the nodes in order to ensure high quality data transmission and the nodes radio transmission power can be reduced enlarging their batteries lifetime. The video in [29] shows a "data mule" experiment carried out outdoors.

Adopting a similar software architecture to that in Section III, we have developed and experimented a WSN data collection method with a fixed-wing Unmanned Aerial Vehicle (UAV), Fig. 12, [30]. In some scenarios UAVs have better accessibility than ground robots. The developed and experimented technique is as follows: a WSN clustering method is used to group the nodes deployed so that a certain data collection performance can be ensured. A node collection zone is defined for each cluster. Then, a Particle Filter path planning method is used to determine a UAV trajectory that flies through the node collection zones taking into account the effect of wind and other perturbations and avoiding forbidden flight zones if any. A brief video of these experiments can be observed at [31]. Although some experiments have been carried out, the full integration of UAVs in the testbed is object of current research.

Fig. 12. Piper UAV in a WSN data collection experiment.

V. Conclusions and Future Works

The paper presents a general integrated testbed for the cooperation of robots, WSNs and other Cooperating Objects. Its objective is to facilitate and accelerate the development, validation and comparison of algorithms, techniques and applications involving heterogeneous COs.

The testbed currently comprises 6 mobile robots (5 *Pioneer 3AT* and one outdoor robot) and 40 static WSN nodes equipped with cameras (IEEE1394 and embedded WSN cameras), laser rangers, and other sensors. The indoor testbed infrastructure includes a vision-based ground truth system, modules for experiment monitoring and logging, IP cameras for visualization and a web server for remote experiment allocation and monitoring through the Internet.

Its modular and flexible software architecture considers all COs at the same level allowing the performance of a wide range of experiments. Currently in operation, the main experiments already carried out focused on cooperative perception using different approaches and robot-WSN collaboration for network repairing.

The development of a suitable integrated simulation tool for heterogeneous COs to complement the testbed, its extension to other COs, e.g. UAVs, and its combination with other existing testbeds are object of current research.

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