INSTITUTE FOR SYSTEMS AND ROBOTICS – LISBON

2008–2013

CONTENTS

PRESIDENT FOREWORD

The Institute for Systems and Robotics–Lisbon (ISR–Lisbon) was founded in 1992. Ever since that date, twenty one years of work, projects, dreams and many achievements have happened. In the meantime, hundreds of young people from different nationalities went through the institution and took the first steps in this difficult but very rewarding adventure of scientific research, learning to deal with uncertainty and accepting challenging targets, while developing practices of rigor and intellectual honesty, in an environment where the debate and confrontation of ideas and opinions is heavily stimulated.

Some of them are fortunately still with us, but many others are now, also fortunately, researchers and teachers in the best universities and scientific institutions around the world, in the United States, Europe, Asia and Oceania. Others help their countries develop, creating companies or integrating existing ones, fostering innovation in products and processes, or promoting the modernization of the public administration.

This brochure is somehow an attempt to show what, after these 20 years, has established itself in the institution. It is not an exhaustive or descriptive approach to all that was or is today important at ISR–Lisbon. The accumulation made and the virtuosities and potential created are such that it would be impossible to constrain them all in a document that by its nature and objectives should be limited to essentials.

I wish to salute those who had the idea and thank all those who contributed to its implementation. ISR–Lisbon is part of a larger research institution (LARSyS) that I will challenge to prepare a similar brochure to display its overall activities soon.

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João Sentieiro
(President of ISR–Lisbon)

RESEARCH THEMES

" Research at ISR–Lisbon spans a multitude of key topics, ranging from fundamental theoretical issues to the applications of engineering methods and tools to the design and analysis of complex systems. "

Research at ISR–Lisbon spans a multitude of key topics, ranging from fundamental theoretical issues to the applications of engineering methods and tools to the design and analysis of complex systems. Across this broad spectrum our methodologies are rooted in solid mathematical principles, providing, whenever possible, formal guarantees of performance.

ISR–Lisbon is one of the R&D units of the Laboratory of Robotics and Systems in Engineering and Science (LARSyS), and most of its research matches the main objectives and the research plan of this national Associate Laboratory. Such objectives and plan embody in their structure a strategy that hinges upon three main lines of action: science, technology, and interaction with society and industry, all sharing a systems approach to research using tools that borrow from solid mathematical theory. This tripartite structure stimulates the cross-fertilization of ideas, motivates challenging problems, and creates further motivation for inter-disciplinary work with scientists from other complementary areas such as natural and/or social sciences.

The application themes of our research address grand challenges whose solutions have strong societal and economic potential impacts, and pose scientific and technological problems of major magnitude. In particular, ISR–Lisbon research focuses on technological solutions for problems within the scope of the open oceans and the deep sea, sustainable urban systems, and biomedicine.

This diversity of applications, the range of research topics covered, and the relevance given to human capital, are distinguishing features of ISR–Lisbon that constitute its hallmark. Some common problems are

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easily identified. One such example concerns sensor and actuator networks, used to monitor the oceans or urban spaces for a myriad of environmental variables. The complexity of such networks raises optimization problems (e.g., sensor placement, coverage, etc.) that require new mathematical results and algorithms. The inclusion of robots as actuators brings to the scene fascinating problems faced by robotic system designers today, from navigation to task planning and execution, interaction and cooperation with humans and other robots. These capabilities turn the networks into active aerial, land, and sea entities where monitoring and surveillance performance can be dynamically improved by moving the robots to adjust the network geometry. Solving these problems requires the ability to blend harmonically contributions from signal, systems and control theories, engineering and computer science fields such as computer vision, artificial intelligence, or the theory of computation, often resorting to inspiration drawn from the natural and social sciences. Another example lies in the bilateral relationship of robotics with the biological and biomedical sciences, where robot assistants and robot swarms are used to study models of human and non-human animal behavior, while exploiting bio-inspired methods to improve their natural interaction with humans and advance the state-of-the-art of complex robot systems.

THEMATIC INTERESTS

DYNAMIC SYSTEMS AND CONTROL THEORY

Introduction

Dynamic Systems theory is at the core of the research being done at ISR–Lisbon on a number of subjects pertaining to single and multiple networked robotic vehicle navigation and control, as well as optimization. Multidisciplinary research efforts involving system–theoretic concepts have been pursued with the double objective of: i) understanding key issues and fundamental limitations inherent to system design and ii) developing new tools for the analysis and design of advanced navigation and control systems for autonomous vehicles.

Methodologies

The work done over the years has shed light into a number of problems, the solution of which is central to the development and operation of networked autonomous robots for air, land, and marine applications. Namely, single and cooperative vehicle control in the presence of stringent communication constraints, multiple vehicle motion planning, sensor based control (including docking and homing for underwater vehicles as well as range–based fleet formation control), automatic take off and landing of autonomous aircraft, and a number of estimation problems that include single beacon navigation, source localization, and cooperative geophysical–based navigation. Theoretical work on multiple model adaptive robust control pioneered by Prof. Michael Athans has progressed to the level where some of the algorithms for dynamic positioning of marine vessels subjected to the influence of waves developed in cooperation with researchers at the NTNU, Norway have been successfully tested in a water basin.

On a different and yet related vein, challenging issues on dynamical modeling of biological systems have also been addressed. Prof. Athans has been a key promoter of the

collaboration with systems biologists, which has led to a novel approach to the study of the dynamics of the molecule expression level of large-size cell populations using a stochastic hybrid automaton framework.

Emergent Topics

Current research on system theoretical issues is focused on: robust multivariable control synthesis, model predictive control, distributed and decentralized estimation and control systems, hybrid systems, adaptive control using multiple-model concepts and hierarchical systems, and sensor-based cooperative motion control. Interdisciplinary research is also being done on a number of topics that include the modeling of the human immune system using hybrid system concepts and the human vision system by resorting to hierarchical estimation methodologies.
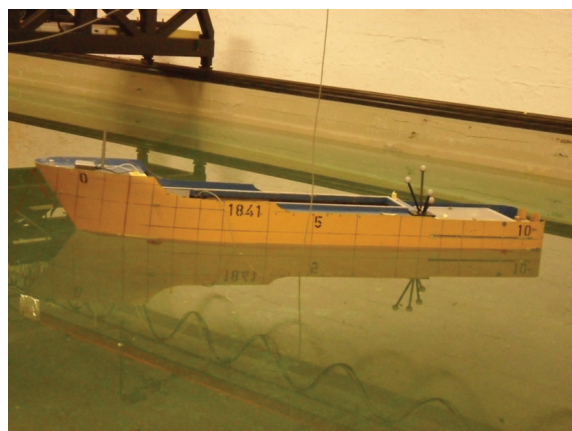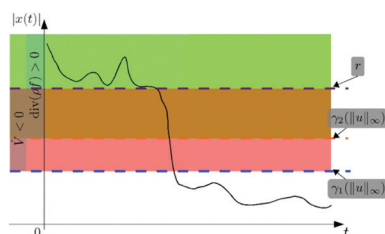
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DISCRETE EVENT BASED PLANNING AND SCHEDULING

> **Discrete event systems are discrete state space systems driven by events, not by time directly. They represent an adequate tool to model, analyze and synthesize systems with such characteristics and their controllers/supervisors.**

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Introduction

Discrete event systems are discrete state space systems driven by events, not by time directly. They represent an adequate tool to model, analyze and synthesize systems with such characteristics and their controllers/supervisors. Examples are the representation of robot plans, and their execution by a Mission Control System (MCS), but also the management of water irrigation channels or railway traffic. The analysis may refer to logical/qualitative properties (e.g., existence of deadlocks, bounded use of resources) or performance/quantitative properties (e.g., plan reliability, plan robustness to the uncertainty of some of its primitive actions). The latter concerns also the development of theoretical results on topics of current interest in the literature, such as Markov chains and queueing systems.

Methodologies + Emergent Topics

At ISR-Lisbon, substantial work has been developed in the last 6 years on modeling robot task plans using Petri nets. Our approach enables modeling a robot task, analyzing its qualitative and quantitative properties and using the Petri net representation for actual plan execution. The overall model is obtained from the composition of simple models, leading to a modular approach that enables building and analyzing complex plans from small Petri net models of primitive actions. Analysis is applied to a closed loop between the robot controller and the environment Petri net models. The quantitative properties are captured by stochastic Petri nets. Furthermore, we introduced a method to identify the environment and action layer parameters of the stochastic Petri net models from real data, improving the significance of the model. In related work, we proposed a methodology to build a Petri net realization of a supervisor that, given a Petri net model of a (multi)- robot system and Linear
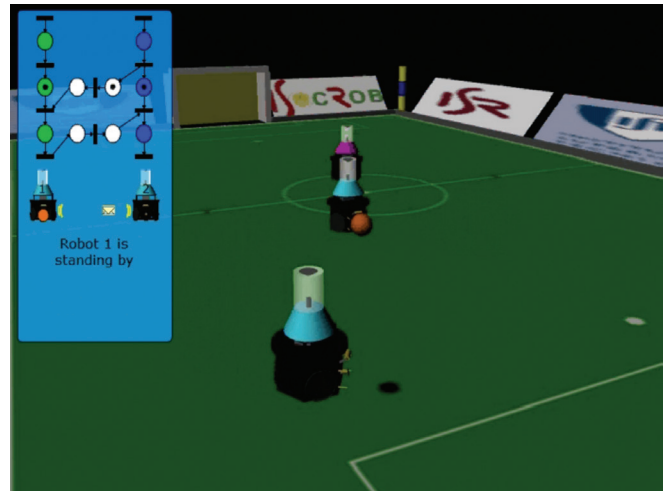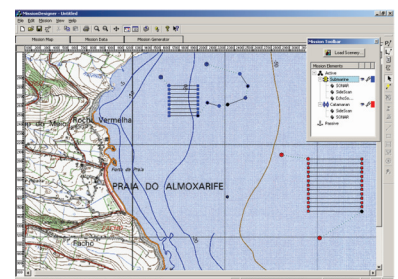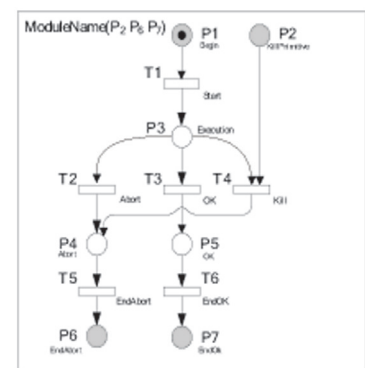
Temporal Logic specifications, forces the system to fulfill them. A Petri net based methodology was also developed to model and execute coordinated missions involving multiple vehicles. In the proposed technique the individual vehicle missions are defined by means of Petri nets and three constraints are added for coordination purposes: mutual exclusion, ordering and synchronization. The proposed methodology generates a centralized net, checks if it is deadlock free and then obtains a decentralized Petri net for every vehicle, minimizing the communications among them. The resulting Petri nets implement the multi-vehicle mission control program that is responsible for coordinating in real-time the set of vehicles involved in the mission.

Programming the behavior of multi-robot systems is a challenging task, which has a key role in developing effective systems in many application domains. We have collaborated with the U. Rome "La Sapienza" on developing Petri Net Plans (PNPs), a language based on Petri Nets, which allows for intuitive and effective robot and multi-robot behavior design. PNPs are very expressive and support a rich set of features that are critical to develop robotic applications, including sensing, interrupts and concurrency. As a central feature, PNPs allow for a formal analysis of plans based on standard Petri net tools. Moreover, PNPs are suitable for modeling multi-robot systems and the developed behaviors can be executed in a distributed setting, while preserving the properties of the modeled system. PNPs have been deployed in several robotic platforms in different application domains.

GUIDANCE, NAVIGATION, AND CONTROL SYSTEMS

> *The plethora of mission objectives, platforms, actuation systems, coupled with theoretical and practical challenges, renders the motion control of autonomous vehicles a great and stimulating area of research.*

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Introduction

In the recent past several sophisticated autonomous vehicles and robotic platforms have been developed, endowing the scientific community and the industry with cutting-edge research and exploration tools. The ability to operate in potentially hazardous scenarios, without putting human lives at risk, is one of the strongest driving forces behind this trend, along with the capability to perform fully automatic complex, thorough and exhaustive tasks. Other reasons include lower construction and operational costs, enhanced performances, faster deployment times, increased agility, greater flexibility, reduced maintenance and, naturally, the wide spectrum of operation scenarios, that range from ground to aerial, space, or marine environments. The guidance, navigation, and control systems ensure the correct localization and motion control of these autonomous systems and are thus vital to their successful operation.

Methodologies + Emergent Topics

The navigation system is responsible for the correct determination of the vehicle pose (position and attitude) and velocity. To that purpose, data obtained from multiple sensors that are installed on-board, such as Inertial Measurement Units (IMUs), aided by external positioning systems such as the Global Positioning System (GPS), are fused using kinematic and/or dynamic models of the motion of the vehicle. This is a very active topic of research, with the pursuit of optimal solutions with theoretical guarantees such as globally asymptotically stable (GAS) error dynamics. The plethora of mission objectives, platforms, actuation systems, coupled with theoretical and practical challenges, renders the motion control of autonomous vehicles a great and stimulating area of research. While

the control of linear systems is generally well understood, there are still many interesting questions related to the control of autonomous vehicles springing from, e.g., the lack of coupled experimentally validated dynamic models, the inability to readily identify plant parameters, which exhibit, in general, strong nonlinear behaviors, or the often underactuated nature of these vehicles. These elements hence force solid integrated guidance and control approaches, based on novel theoretical foundations, which guarantee stability properties and good performance in the presence of sensor noise, coupled with robustness to unmodeled dynamics. Advanced guidance and control are also at the core of advanced systems to enable cooperative motion control of groups of air and marine.

The variety of vehicles, sensors, actuators, guidance, navigation and control strategies, and mission objectives, together with the fact that these systems must be robust and failsafe, ensure nowadays a vast and prolific field of active research, with the pursuit of novel robust and optimal approaches. At ISR-Lisbon we continue to be highly committed to achieve and improve on these goals, developing and evaluating the performance of novel solutions, not only in simulation but also with the development and test of prototypes, involving strong multidisciplinary teams.

IMAGE ANALYSIS AND COMPUTER VISION

> *Our activities share the interest of automatically extracting useful information from images.*

Introduction

There are thousands of images in the Internet and hundreds of cameras in public infrastructures. Many people carry cameras, taking photographs of friends and places, and we also receive images from space probes. Our activities share the interest of automatically extracting useful information from images. While the images range from ordinary video to those obtained with non–conventional cameras, the information to extract includes: contours of moving objects, 3D models of the world, motion patterns for surveillance, shape and texture for remote sensing, and descriptors for image recognition.

Methodologies + Emergent Topics
Image Recognition and Retrieval

Several applications require identifying instances of objects in images (e.g., robot vision) or categorizing general image patterns (e.g., browsing the Internet). A common approach to these problems consists of computing a set of local descriptors from the images and comparing them with previous models.

We have contributed to this trend in several directions. Inspired by the complex cells in the human brain, we have developed image analysis (Gabor) filters to improve recognition ability. We have proposed novel descriptors, based on complex moments, which have the distinguishing features of being invariant to rotation, discriminative, and compact (of outmost relevance when dealing with large databases). Matrix completion and rank minimization principles have been successfully applied to multi–class, multi–label recognition. We have also implemented, in several robotic platforms, novel real–time object similarity metrics, shown to be robust to partial occlusion.
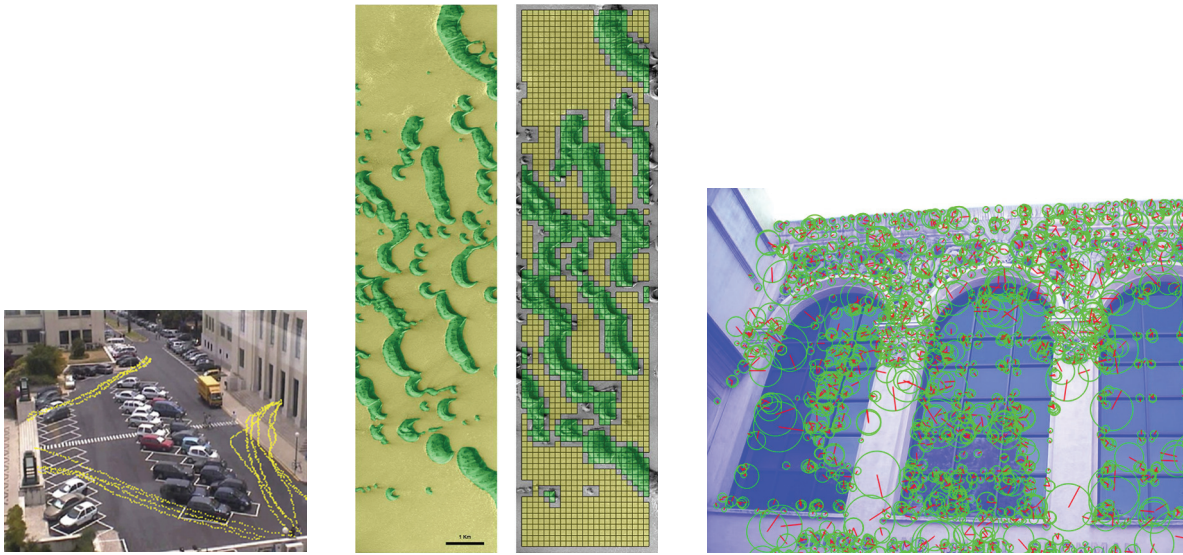
3D Structure from Video

Applications ranging from robotics to virtual reality need 3D models of world scenes. When inferring 3D models from images, determining which image point corresponds to each 3D point, is key for the success. Contrasting with methods that attempt to solve this problem in a pointwise local way, we exploit global constraints, e.g., scene rigidity, and develop techniques to compute the optimal solution to the set of point correspondences.

Inferring 3D from images requires solving a complex optimization problem, which has been successfully addressed through the matrix factorization method, which uses optimality properties of the SVD of an observation matrix whose entries are point trajectories. We have contributed to the matrix factorization method, including dealing with architectural scenes, multiple objects, and developable and articulated shapes. A major achievement was an optimal method to deal with occlusion, situation in which several points disappear, originating an incomplete observation matrix, whose SVD can not be computed. Our method determines the optimal completion of the matrix in a finite number of steps.

Non–conventional Cameras

The diversity of the biological world shows many animals that have specialized vision systems. This contrasts with conventional video cameras, which simply use CCD sensors and narrow field–of–view lenses. Our research on non–conventional cameras encompasses several paradigms, including: the combination of reflective surfaces with lenses, CCDs with non–uniform resolution and sensibility to non–visible light, aggregation of multiple cameras, and light pattern projection.

We have developed human–eye inspired sensors, targeted to object tracking, and omnidirectional sensors, used for robot navigation. A relevant issue is the calibration of such systems, which, due to the unknown (and irregular) sensor topology, has to be performed by using specialized methods. We introduced innovative ways to exploit properties of natural scenes for the calibration of these systems. Our work has demonstrated that, in many applications, it results advantageous to modify or create novel cameras, paving the way to the
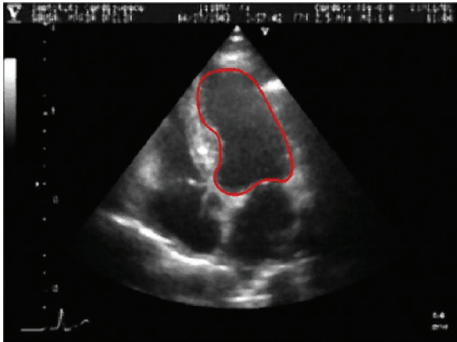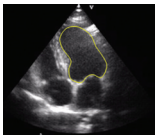
development of cheaper and smaller future computer vision systems.

Segmentation and Tracking

Image segmentation aims to extract the boundaries of objects in images, a first step required by several image analysis systems. The major challenges concern dealing with a large variety of object shapes and visual aspects, as well as with cluttered backgrounds. The problem becomes easier when dealing with video, so that the temporal evolution of the object boundary can be exploited.

As in many image and video analysis problems, segmentation and tracking methods are prone to failures when the models deviate from reality. Motivated by these difficulties, we have worked on robust methods for segmentation and tracking. In particular, we have developed new deformable models and algorithms that incorporate the knowledge that most of the

features detected in the image are outliers, thus should not be trusted. This knowledge is exploited to improve the robustness of the segmentation and tracking methods, making them able to cope with cluttered backgrounds and outliers.

Surveillance

There are many cameras deployed in public infrastructures (e.g., airports or train stations). However, since it is not possible to guarantee a real-time analysis of this information by human operators, most of it is only used a posteriori, to enable visualizing past events. Large efforts have recently been made to improve surveillance systems and to automate tasks such as people and vehicle tracking, abnormal events detection, and activity recognition.

We have participated in this effort, addressing large infrastructures. Indoors, analysis of the trajectories of people and their spatio-temporal

features enabled the recognition of human activities. Outdoors, we have studied vehicle tracking and analysis in cities and highways, as well as people tracking and behavior recognition. In such cases, trajectory analysis plays a key role. We have developed trajectory clustering algorithms, as well as new stochastic models, based on multiple motion fields, to recognize typical activities and detect abnormal ones.

Remote Sensing

In remote sensing, we process signals acquired by sensors mounted on satellites, aircrafts, or telescopes, which usually capture several wavelengths of the electromagnetic spectrum. Our work has focused on processing satellite images of the Earth and Mars.

With the goal of automatically distinguishing water from land in the Earth, we have used SAR images. These images are challenging due to speckle,

a multiplicative noise that produces a ''grainy'' appearance, which prevents the usage of many common segmentation methods. To cope with this difficulty, we have developed a new region-based method, based on level sets and a mixture of lognormal densities.

Images of Mars have been analyzed in order to detect structures such as craters and dunes. In the case of the detection of dunes, this was is the very first attempt to automate the operation. Our pattern recognition methods achieved state of the art results in automatically detecting such structures.
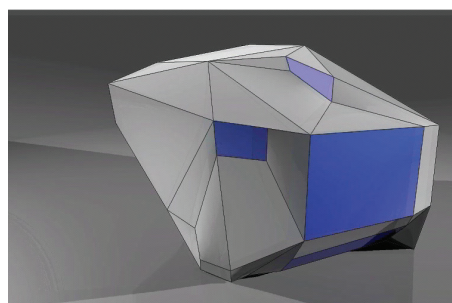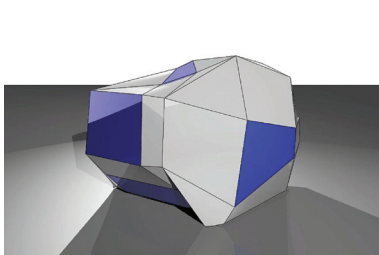
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BIOLOGICAL AND MEDICAL SIGNAL PROCESSING

In this research line, Biomedical data processing and information extraction from different medical and biological modalities are addressed, mainly in the scope of Computer Aided Diagnosis (CAD), Computer Aided Therapy (CAT) and Computer Assisted Surgery (CAS) applications.

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Introduction

In this research line, Biomedical data processing and information extraction from different medical and biological modalities are addressed, mainly in the scope of Computer Aided Diagnosis (CAD), Computer Aided Therapy (CAT) and Computer Assisted Surgery (CAS) applications.

From a methodological point of view, statistical approaches and data mining techniques for modeling, signal processing and classification of biological and medical data are the preferred tools. Physiological, Clinical and Behavioral data are mainly obtained from electro-encephalographic (EEG), Electrocardiographic (ECG), Actigraphy and Polysomnography (PSG) 1D signals as well as from Biological and Medical image modalities such as Magnetic Resonance Imaging (MRI), functional MRI, Ultrasound and Fluorescence Microscopy.

Methodologies + Emergent Topics

Symbolic representation of the Sleep EEG from Polysomnography recordings

In this work a symbolic representation of sleep EEG signals is obtained based on frequency composition. It provides simultaneously significant background and transient responses. Two symbolic representations were proposed: FS0 basic frequency composition symbols and FS1 sequential association.

Characterization of the Carotid Atherosclerotic disease from Ultrasound and Clinical Data

This project aims at developing an ultrasound-based diagnostic measure to quantify atherosclerotic plaque activity. The method is rooted on the identification of an "active" plaque profile containing the most relevant ultrasound parameters associated with symptoms. This information is used to build an Enhanced Activity Index (EAI) which considers the conditional probabilities
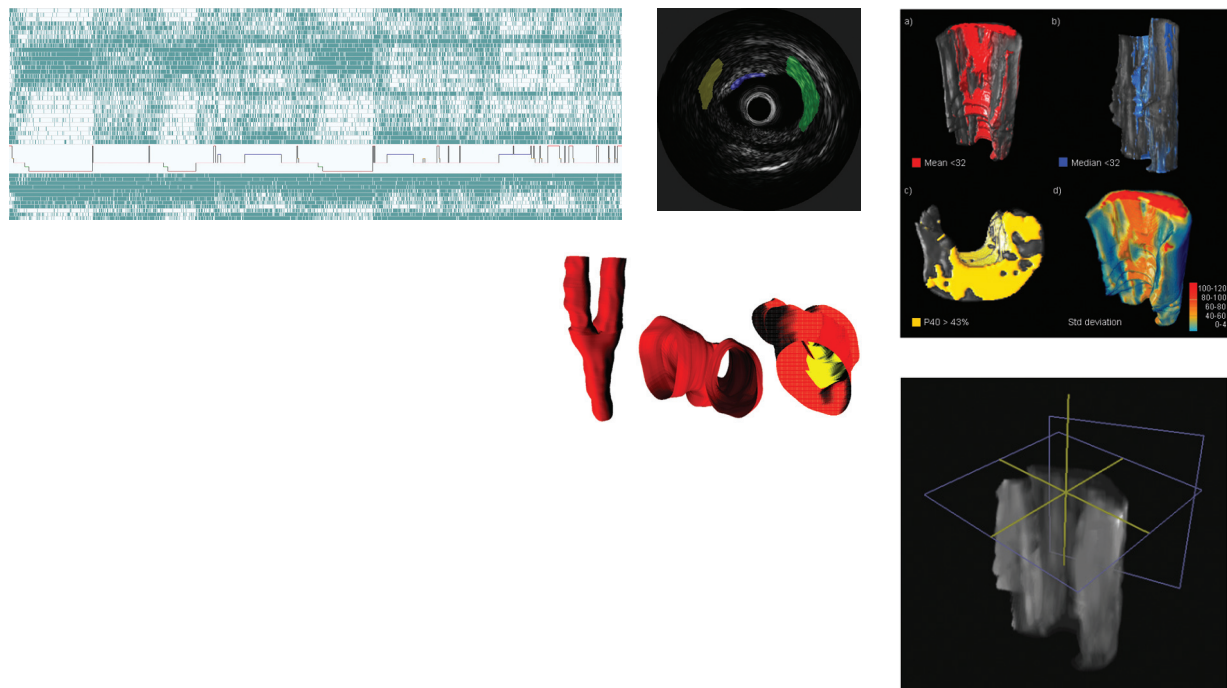
of each relevant feature belonging to either symptomatic or asymptomatic groups.

Computer Aided Diagnosis of the Hepatic Disease from multimodal medical data

The main goal of this project is the identification and diagnosis of various stages of chronic liver disease. Several classifiers are being tested, e.g. support vector machine, a decision tree and a k-nearest neighbor, with multimodal data. Ultrasound image intensity and textural features are jointly used with clinical and laboratorial data in the staging process of the hepatic disease.

Perfusion imaging using ASL MRI

Perfusion measures the rate at which nutrients are delivered by the blood to the tissues in the capillary bed and its accurate measurement is important in the diagnosis and monitoring of different pathological conditions. Arterial Spin Labeling (ASL) techniques offer a non-invasive way of measuring perfusion using MRI, with great potential in clinical practice. However, important methodological challenges must be tackled in order to achieve truly quantitative and reliable measures. The main objective of this line of research is to optimize both the image acquisition and data analysis procedures, using biophysical modeling within a Bayesian framework, and to establish the validity and reproducibility of perfusion measurements in different conditions.

The Segmentation of the Left Ventricle of the Heart from Ultrasound Data using Deep Learning Architectures and Derivative-based Search Methods

In this line of research we propose a new automatic Left Ventricle (LV) segmentation that addresses the following supervised learning model issues: i) avoid the need of a large set of training images, ii) robustness to imaging conditions not present in the training data, and iii) complex search process. In order to handle i) and ii), we rely on the use of deep learning architectures and a new formulation of the LV segmentation that decouples the rigid and non-rigid detections. The complexity issue is addressed with the use of optimization algorithms of first (gradient descent) and second (Newton's method) orders.

COMPUTATIONAL NEUROSCIENCE

" At ISR–Lisbon we span across the several aspects of Computational Neuroscience in an inter–disciplinary approach between life sciences and engineering sciences. "

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Introduction

Computational Neuroscience aims at understanding how the nervous system is able to perceive, learn, reason and act on the real world. Neural mechanisms provide natural systems with skills that are unmatchable in artificial systems and still unexplained by current knowledge. Engineering sciences can play a crucial role uncovering such mechanisms in a two–fold approach: by providing the tools for analyzing and interpreting physiological measurements; and by modeling, simulating and testing neuroscience hypothesis on artificial systems. Ultimately, the results obtained can be exploited for improving our understanding of brain function and disease diagnosis, as well as for augmenting human capabilities and designing more "intelligent" artificial systems. At ISR–Lisbon we span across the several aspects of Computational Neuroscience in an inter–disciplinary approach between life sciences and engineering sciences, as reflected in the following research lines.

## Methodologies + Emergent Topics
Spatiotemporal Dynamics of Epileptic Activity: EEG–fMRI Neuroimaging Investigation

Epilepsy is increasingly recognised as a neurological disease reflecting disturbances within networks of functionally connected brain structures, but understanding their connectivity remains a central problem in epileptology. The main objective of this research line is to study the spatiotemporal dynamics of human brain networks involved in epileptic events recorded using simultaneous EEG-fMRI, in order to elucidate the underlying disease mechanisms and improve the sensitivity and specificity of such non-invasive recordings for clinical applications. Biophysically–inspired models are employed in order to investigate the coupling between EEG and fMRI signals and the propagation of epileptic activity throughout extended brain networks, while novel model estimation approaches are proposed.
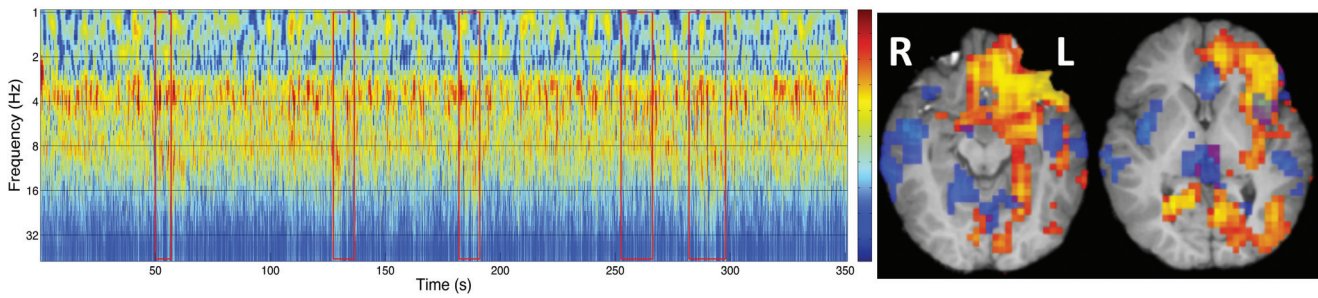
## Modeling and Simulation of Neuroscience Theories in Artificial systems

Many hypotheses about the underlying principles of cognition and intelligence have been suggested by neuroscience and psychology experiments on biological systems. At ISR–Lisbon we draw inspiration from these studies to develop mathematical models for complex perceptual and cognitive processes that are validated through computational and robotics simulations. Paradigmatic examples include modeling the Mirror Neuron system in the macaque brain and illustrating role of Motor Theories of Perception in visual and speech recognition processes; applying biomimetic oculomotor control principles for the development of advances active vision systems; and developing models
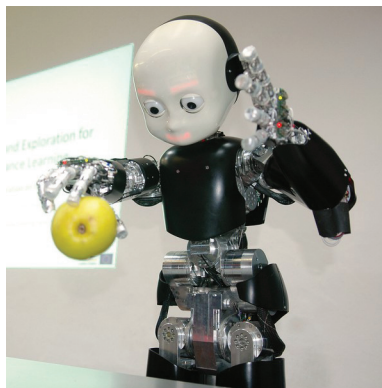
the Theory of Affordances in learning human–object interaction models. Robotics simulations are demonstrated on the advanced humanoid robot platform iCub and available to the scientific community through open source implementations.

Enhancement of Cognitive Performance

Enhancement of Cognitive Performance through self–control of brain oscillations appears to be a very promising non–invasive, non–pharmacological and very low–cost methodology, where therapy for psychological, psychiatric and neurological functional disorders has been envisaged, as well as performance enhancement on healthy subjects. We have developed a real–time system for enhancement of cognitive performance, where advanced features feedback can be provided to the subject in order to learn and practice self–control.
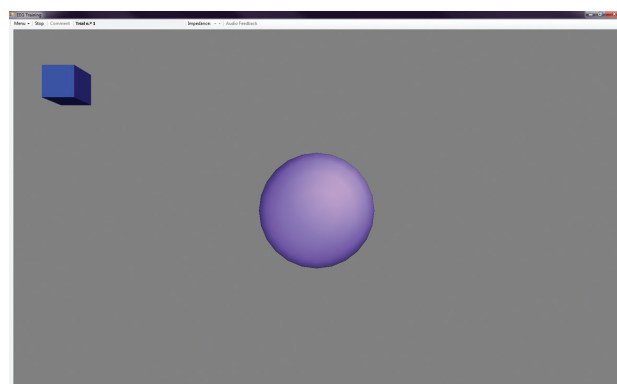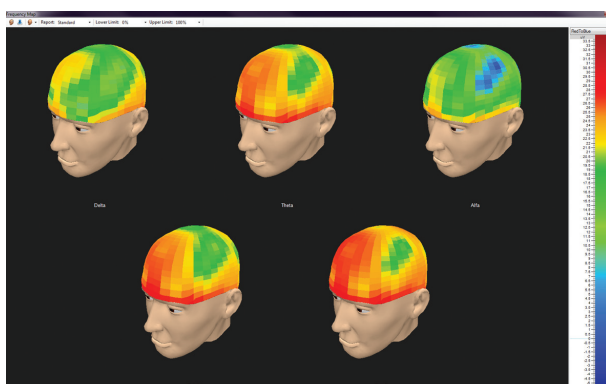
COGNITIVE HUMANOID ROBOTS AND SYSTEMS

> *... cognition refers to the ability of endowing artificial systems (e.g., a PDA or a robot) with the ability to "understand" and reason about the surrounding environment, including the interaction with humans or other artificial systems.*

Introduction

Generally speaking, cognition stands for the "mental action or process of acquiring knowledge and understanding through thought, experience, and the senses". In this scope of the activities developed at ISR–Lisbon, cognition refers to the ability of endowing artificial systems (e.g., a PDA or a robot) with the ability to "understand" and reason about the surrounding environment, including the interaction with humans or other artificial systems.

Methodologies + Emergent Topics

Human activity recognition from video

Video surveillance systems have been deployed in many public infrastructures such as city centers, airports, shopping malls, etc. Needless to say, the massive amount of images produced by this means requires the development of artificial systems able to process all the data and detect important events. In the context of the EU Project CAVIAR we have started the development of vision systems that can not only track humans but also recognize their activities. The systems can learn autonomously over time and adapt different working scenarios. While the context of applica-

tion of this system was mainly in the surveillance area, the methodology can also be used in houses if we want to detect changes to behavior and monitor and assist the elderly in their homes.

Learning by Imitation

Robots have been in use in industry settings for several decades and contributed to an enormous increase in efficiency and quality in many domains. In order to have robots in "normal" spaces, we have to provide them with the capacity of dealing with uncertainty and unpredictable events, including the interaction with humans. The interaction with non-expert humans thus requires intuitive ways of "programming" a robot without the need to write thousands of lines of software. We have developed ways whereby a robot can learn how to execute certain tasks by observing an expert demonstrator. Using vision, the robot can measure and extract parameters that describe the human actions and gestures. Then, using its own motor programs, the robot can perform the tasks without the need of any explicit programming.

Networked robots in urban areas

As mentioned before, ISR–Lisbon researchers aim at contributing to the development of robot skills that will allow them to interact and collaborate with humans in a natural way. In the EU Project URUS, we have worked on the deployment of a networked robot system in urban areas. In addition to the ability to localize and map the surrounding environment, these robots could recognize human gestures and communicate through an ubiquitous communication network to exchange information relevant to the task.

Attention and recognition

It is well known that the perceptual world is so complex that the human brains relies on a number of strategies to focus on the most relevant information and (almost) ignore

the rest. These attention mechanisms allow us to "filter" the world information that is relevant for a certain task, instead of being distracted by superfluous information. We have developed models of automatic attention, whereby humans can vary rapidly and attend to moving objects, salient regions, etc... In addition we also developed methods of so-called top-down attention where the lower-level processes are primed or modulated by higher level information. These methods have been demonstrated on the humanoid robot iCub where the robot can react automatically to perceptual stimuli or search for pre-defined objects in the scene.
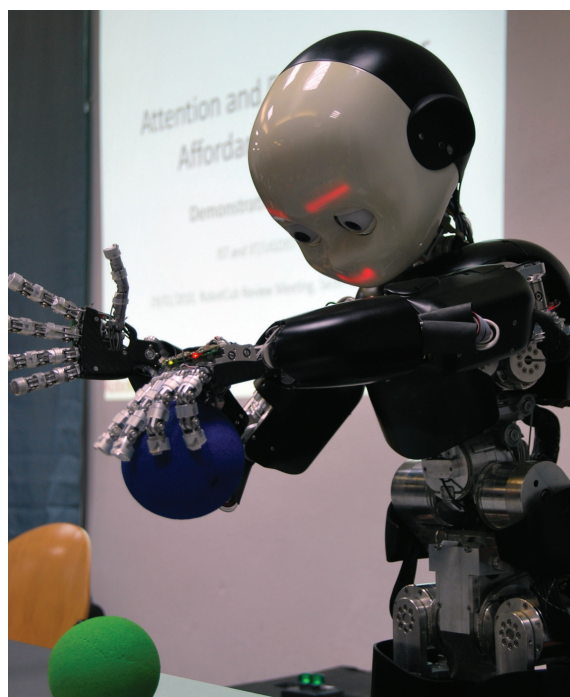
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DISTRIBUTED SIGNAL PROCESSING FOR NETWORKS

> *We considered a generic computational model that captures many applications in networked systems, in which nodes cooperate to find the optimal parameter of common interest.*

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Introduction

Over the past few years, we have witnessed tremendous advances in the miniaturization of low cost electro-mechanical devices that exhibit several sensing capabilities, and possess significant embedded processing and low-range wireless communication. These developments triggered interest in wireless sensor networks (WSN) where large collections of such small sensor nodes are scattered across critical areas to monitor and actuate. Typically, these networks lack a central unit and must rely on fully distributed, collaborative signal processing techniques between the nodes for successful operation. Moreover, in realistic scenarios, the inter-node communication is prone to random failures.

Methodologies + Emergent Topics

We considered a generic computational model that captures many applications in networked systems, in which nodes cooperate to find the optimal parameter of common interest. Each node has a private convex cost function of the parameter. The total cost is the sum over the individual nodes' costs. Nodes follow a gossip protocol to communicate through a generic connected network with asymmetric failing links. We proposed a novel distributed optimization algorithm, based on augmented Lagrangian duality. We established convergence of our algorithm in the face of asymmetric link failures, and applied it in L1-regularized logistic regression for distributed learning applications, and cooperative spectrum sensing for cognitive radio systems.

We studied the performance of the consensus+ innovations distributed detector over networks
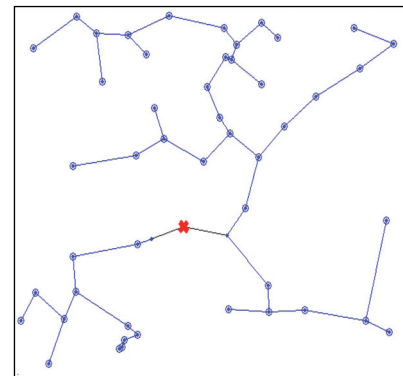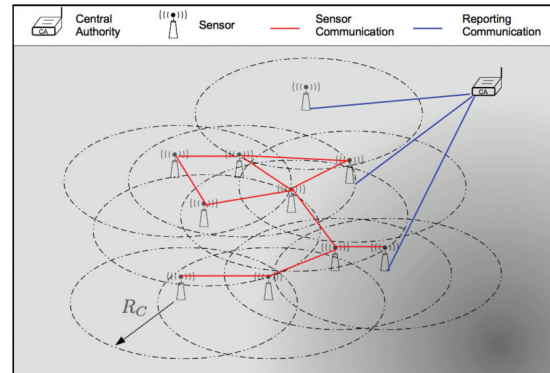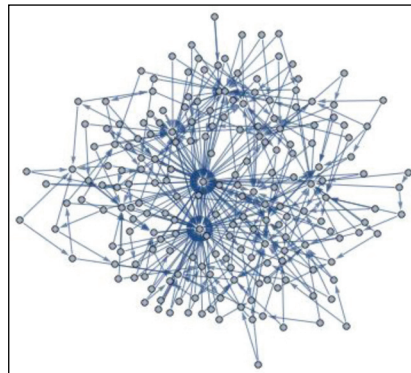
with random link failures, where each sensor, at each time step, weight averages its decision variable with its neighbors decision variables (consensus), and accounts on-the-fly for its new observation (innovation). The degree of connectivity of the random communication topology is suitably represented by a single parameter, hereafter referred as DNC (degree of network connectivity). Using large deviations analysis, we discovered that distributed detection exhibits a phase transition behavior with respect to DNC: when DNC is above a threshold (which we quantify), distributed detection is equivalent to the optimal centralized detector which has access to the totality of all sensor observations, i.e., the detection probability of error decays exponentially (at each sensor) at the same rate as in the centralized detector. When DNC is below the threshold, we also have found the achievable error exponent of the distributed detector.

A particular emerging area in game-theoretic methods for the analysis of networked systems is mean field games, which will likely have a wide application in sensor networks and distributed systems that involve a large number of agents or players. This mathematical framework is suitable to model and analyze the behavior of games among N agents, in the limit, (when N converges to infinity) and relies on the fact that the interaction between the agents is modeled by an interaction of each individual agent with a mean field, which represents the effects off all the other players. It turns out that the framework generalizes optimal control problems by allowing the cost function of each agent to also depend on the density function for all other agents and due to that it has the potential to offer new insights for more robust algorithms.

DISTRIBUTED ROBOTIC SYSTEMS

> **Distributed Robotic Systems comprehend the methods and techniques to manage a set of actuating and sensing devices, including robots, connected under heterogeneous forms.**

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Introduction

Distributed Robotic Systems comprehend the methods and techniques to manage a set of actuating and sensing devices, including robots, connected under heterogeneous forms. The underlying idea is that a monolithic structure can be distributed as a network, improving efficiency, performance, reconfigurability and robustness. Potential applications include search and rescue, surveillance and surveying operations, remote observation, and exploration in hazardous environments.

Methodologies + Emergent Topics

Methods to generate online paths to be followed by multiple vehicles so as to optimize a given mission goal were also introduced. The cost criteria may include travel time or energy expenditure. The path planning methods take into account issues such as inter-vehicle collision avoidance and simultaneous times of arrival, and are computationally suitable to real-time applications. A path-following control law has also been designed to drive each vehicle to its assigned path. The speeds of the virtual targets are adjusted about their nominal values so as to synchronize their positions and achieve vehicle coordination. It is explicitly considered that each vehicle transmits its state to a subset of the other vehicles according to a communications topology. Conditions are derived under which the path following and the coordination errors are driven to a neighborhood of zero in the presence of communication losses and time delays.

An integrated approach to Guidance, Navigation and Control of formation flying spacecraft was introduced, within a study funded by ESA, to handle the periodic computation of the state

of each individual autonomous vehicle by using a shared network to transmit data, eventually under communication constraints. An algebraic closed-loop algorithm was proposed for the Guidance and Control subsystem of a 3-spacecraft mission, minimizing the propellant consumption and ensuring collision avoidance and providing the optimal trajectories and the optimal control inputs. A full-order decentralized filter implements the Navigation algorithm, estimating the full state of the involved spacecraft. The algorithm is based on an Extended Kalman Filter (EKF) for local measurements, and on a Covariance Intersection algorithm (plus the EKF prediction part) for the fusion between local state estimates and state estimates communicated by other spacecraft.

We have carried out substantial research on decision-theoretic decentralized planning under uncertainty for networked robot systems (NRS), in which mobile robots carrying sensors interact with each other as well as with static sensors present in the environment to accomplish certain tasks. For instance, in a shopping mall, we can consider a NRS where cameras detect humans in need of help, but also detect a fire eruption requiring assistance. Robots can be used both to improve the confidence on the event detection and to provide assistance for any of the above situations, depending on the evaluation of the event detection confidence vs event priority tradeoff. Mobile robots with onboard sensors are also key elements of active cooperative perception, where the goal is to maximize the amount and quality of perceptual information available to the system by selecting actions for moving sensors that take them to viewpoints that yield more information.

An open-loop optimal control law for robot swarms has been introduced, where a stochastic hybrid automaton models the swarm state controlled dynamics. The dynamics of the state probability density functions was determined and an optimal control problem of maximizing the probability of robotic presence in a given region was solved.
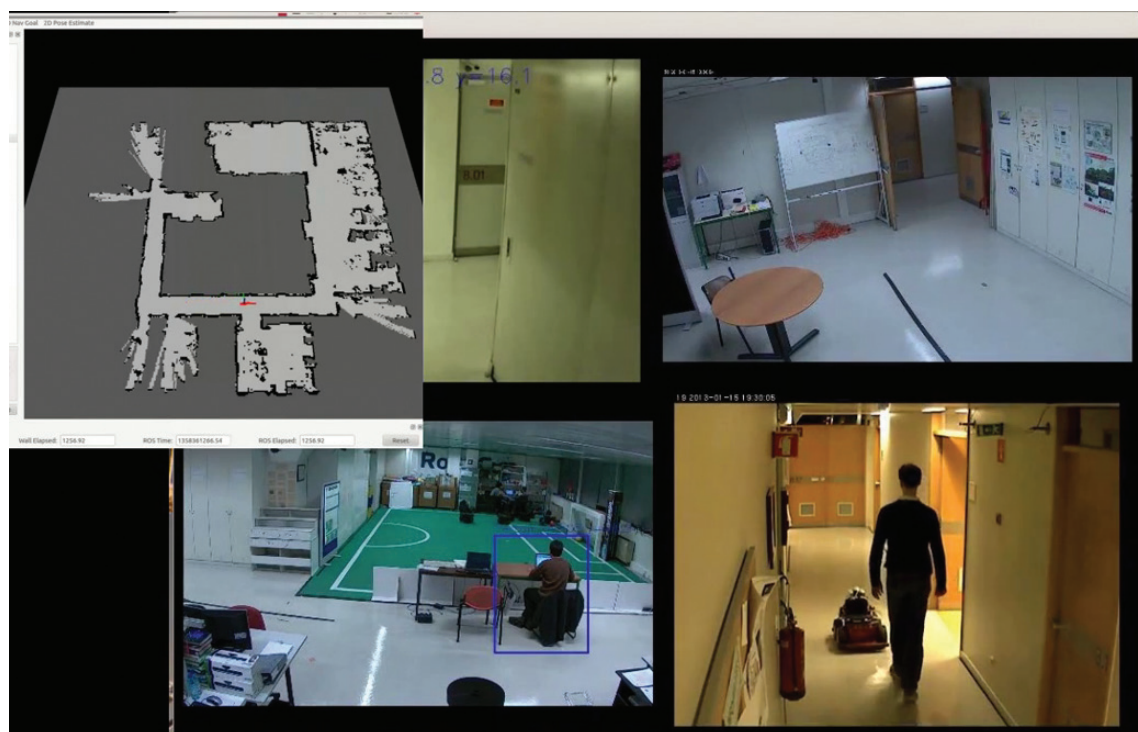
OCEANIC ROBOTICS AND SYSTEMS

> *Pioneering work at ISR–Lisbon, done in the scope of a large a number of European and Portuguese funded projects, has led to the design, development, and operation of a fleet of autonomous surface and underwater vehicles, supported by several positioning and tracking systems tailored for several applications that range from surveying,*

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Introduction

Over the past decades, there has been tremendous progress towards the development of advanced robots and systems for commercial and scientific operations at sea. The wide spread use of autonomous marine vehicles avoids placing human lives at risk and allows access to otherwise unreachable regions of the ocean. Equipped with advanced systems for navigation, guidance, control, and scientific data acquisition, these vehicles are steadily affording scientists advanced tools to drastically simplify the task of acquiring cost-effective ocean data timely, without constant supervision of human operators.

Methodologies + Emergent Topics

Since the early days at ISR-Lisbon, a set of problems of interest in ocean applications have been pursued resorting firstly to a physics based formulation associated with state-of-the-art theoretical tools, well rooted in such fields as systems' theory, decision and estimation theory, telecommunications, discrete event systems, and biology. Dynamic systems theory has proven to be a rich methodology and a supporting set of mathematical principles and tools for the analysis and design of navigation, guidance, and control systems for robotic vehicles. From the point of view of systems implementation, the solutions pursued exploit heavily fast paced developments in the area of embedded systems and computer networks.

Pioneering work at ISR-Lisbon, done in the scope of a large a number of European and Portuguese funded projects, has led to the design, development, and operation of a fleet of autonomous surface and underwater vehicles, supported by several positioning and tracking systems tailored for several applications that range from surveying,
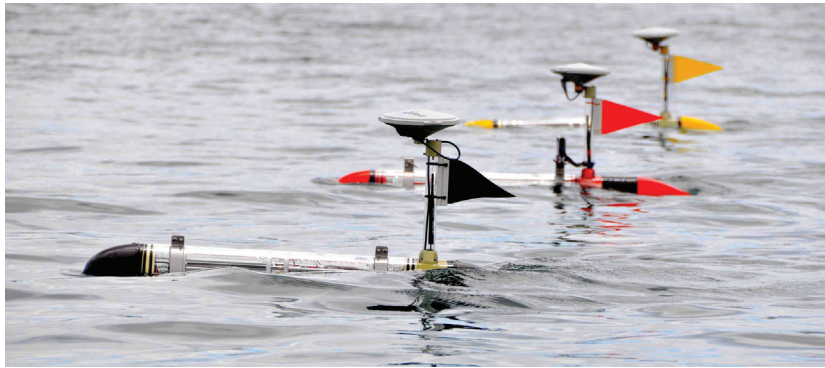
surveillance, and marine archeology to intervention and environmental studies. One such example is the Underwater Acoustic Network (UAN) FP7-project, where a full underwater acoustic network with fixed and AUV mounted mobile nodes aiming at the protection of off-shore and coastline critical infrastructures was developed and tested at sea. A full deployment sea trial took place in May 2011 in the Trondheim Fjord (Norway) and showed for the first time, in real conditions, the effectiveness of all the network layers from the physical layer up to the Command and Control layer.

Another line of research pursued in close collaboration with the researchers of DOP/UAçores, has been the technological development of specific instrumentation suited to the study of ecosystems found in the deep ocean. Emission of fluids (cold seeps, hydrothermal vents), existence peculiar topographic structures (seamounts, deep corals), massive organic inputs (sunken woods) or to unpredictable events (pollution, earthquakes), have been some of the phenomena that were studied, requiring the use of submersibles able to work at reduced scales on the seafloor as well as the development

of autonomous instruments for long-term monitoring (seafloor observatories).

These efforts have led naturally to the development of robots and systems with far reaching impact on a number of audiences including: i) scientists and experts in the field of marine science and technology; ii) institutions with an active role in the exploration and exploitation of the sea; and iii) the public at large. These activities have also fostered new graduate and undergraduate academic curricula in the challenging and multidisciplinary areas of marine science and robotics.

AERIAL ROBOTICS AND SYSTEMS

> *... our research activities have focused on developing and demonstrating the benefits of using a sensor-based approach to address the problem of motion control of Unmanned Aerial Vehicles (UAV), to perform tasks that require a reactive and compliant behavior in clotted and uncertain environments.*

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Introduction

Aerial Robotics is an emerging field of research, full of challenges and potential. Currently, the field is witnessing an increasing interest in operation scenarios that involve close interaction between the aerial vehicles and the surrounding environment. In this context, our research activities have focused on developing and demonstrating the benefits of using a sensor-based approach to address the problem of motion control of Unmanned Aerial Vehicles (UAV), to perform tasks that require a reactive and compliant behavior in clotted and uncertain environments.

Targeted applications, which have been a driving force underlying our work, include the inspection of critical infrastructure, such as bridges, dams, power plants, dams, and the monitoring of cetaceans and schools of large fish.

Methodologies + Emergent Topics

Within the scope of projects that address the aforementioned applications, we have addressed the problems of trajectory tracking and path following control of rotorcraft, exploring both LPV control and Lyapunov-based nonlinear techniques and taking into account important properties such as robustness to external disturbances and actuation boundedness. Rotorcraft dynamic modeling has also been a topic of research. A simple yet accurate dynamic model, which is specially tailored for model-scale helicopters, has been derived from first-principles and implemented in a simulation environment to provide a tool for the design and evaluation of flight control systems.

Recent work has focused on the problem of position and attitude stabilization for systems evolving on SE(3). Working directly on SE(3) as opposed to adopting a local parametrization has the

advantage of avoiding singularities and unwinding behavior of the systems trajectories, and allowing for the definition of almost globally stabilizing feedback laws. The proposed solution is defined on a setup of practical significance. It is assumed that the position of a collection of landmarks is provided to the system in body coordinates. This type of measurements is typically produced by on-board sensors, such as CCD cameras, laser scanners, pseudo-GPS, etc. Building on the landmark-based solution, a vision-based controller for rigid-body stabilization was derived. The key challenge addressed in this work was to find a stabilizing feedback controller that is guaranteed to keep the features visible and simultaneously provide a formal characterization of the region of the attraction for the resulting closed-loop system. The same principles were also explored to address the problem of attitude estimation on SO(3) and provide an experimentally tested attitude observer that uses image measurements from an active pan and tilt camera combined with possibly biased rate-gyro measurements. Exploiting directly the sensor measurements, a stabilizing feedback law was introduced, and exponential convergence to the origin of the estimation errors was shown. Additionally, an active-vision system was proposed that relies on an image-based control law to keep the features in the image plane. Using recent results in geometric numerical integration, a multirate implementation of the observer was proposed, which explores the complementary bandwidth of the sensors. Experimental results obtained with a high-accuracy motion rate table demonstrate the high level of performance attained with the proposed solution.

LAND ROBOTICS

ISR–Lisbon has a long tradition of developing robots of this kind since the early 1990s, including industrial Autonomous Guided Vehicles (AGVs) and robots for competitions. Tricycle–like, differential drive, omnidirectional and tracked wheel vehicles were built and used in several applications.

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Introduction

Land Robotics refers to a wide area of design and development of a plethora of solutions for locomotion, hardware and software integration for robots operating in land indoor and/or outdoor environments. ISR–Lisbon has a long tradition of developing robots of this kind since the early 1990s, including industrial Autonomous Guided Vehicles (AGVs) and robots for competitions. Tricycle-like, differential drive, omnidirectional and tracked wheel vehicles were built and used in several applications.

Methodologies + Emergent Topics

The transportation of ITER (International Thermonuclear Experimental Reactor) components between the reactor facility buildings for maintenance purposes is provided by the Transfer Cask System (TCS), a mobile platform operating autonomously or semi–autonomously (due to the level of component radioactiv¬ity), with large dimensions 8.5x2.62x3.62 m (length x width x height), a maximum weight of 100 tons and a rhombic kinematics configuration. In 1997, a laser–guided vehicle with these characteristics was proposed by ISR–Lisbon in a studied funded by EURATOM, and became the reference design for ITER Remote Handling casks transportation. The TCS moves along optimized trajecto¬ries, constrained by the highly confined spaces and demanding safety requirements. These smooth obstacle–free trajectories are generated by a specific software tool that provides the required flexibility to accommodate future changes in the ITER buildings, to study motion strategies associated with parking logistics and to define the motion of rescue vehicles that may intervene in unexpected situations.

RAPOSA is a family of tracked wheel robots, developed jointly with the IST spinoff IdMind. These robots are designed to operate in outdoors environments hostile to human presence such as debris resulting from the collapse of built structures. Research with RAPOSA includes three

main areas: (1) effective teleoperation, maximizing the situation awareness of the remote human operator (topics include 3D mapping, augmented reality, and immersive teleoperation), (2) adjustable autonomy, where certain operations are performed autonomously by the robot (e.g., stair climbing, vision-based docking), and (3) multi-robot cooperation with other vehicles, such as unmanned aerial vehicles.

Robot competitions have been a drive for the development of indoor land robots at ISR-Lisbon since 1994. Different kinematic structures were designed, implemented and successfully used in multi-task competitions, including a tricycle-like robot, several differential drive robots – one of them with a patented camera + mirror system to enable the robot control online its motion speed and trajectory – and, more recently, omnidirectional 3-wheeled robots. ISR-Lisbon has been competing in the RoboCup middle-size league (MSL). Innovative solutions were introduced in Robo-Cup by our MSL team, namely an omnidirectional catadioptric system that preserves the norm on the robots' ground plane.

Other types of locomotion and manipulation have been subject to attention of the ISR-Lisbon community:

·   Vizzy is wheeled humanoid robot

for mobile manipulation applications. Its human-like head, arms, hands and torso combine with a wheeled platform provide a versatile platform for service and personal robotics with extended manipulation, human-robot interaction and locomotion abilities.

·   ISR-Lisbon-CoBot is a service robot targeted for office environments, focused on the interaction with humans in a natural way, using speech and tactile interfaces. The ongoing research using this platform aims at a robot capable of executing tasks requested by users, as well as being capable to autonomously ask humans for help.
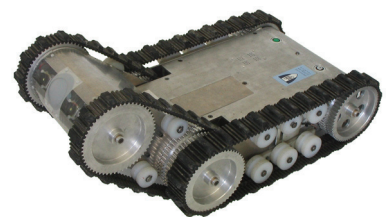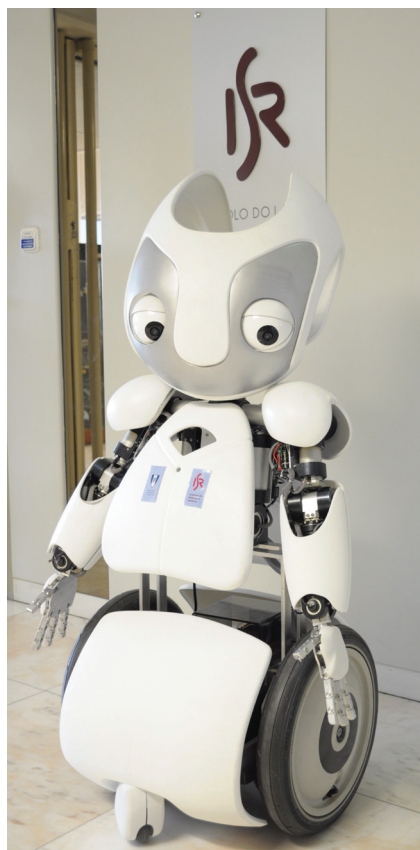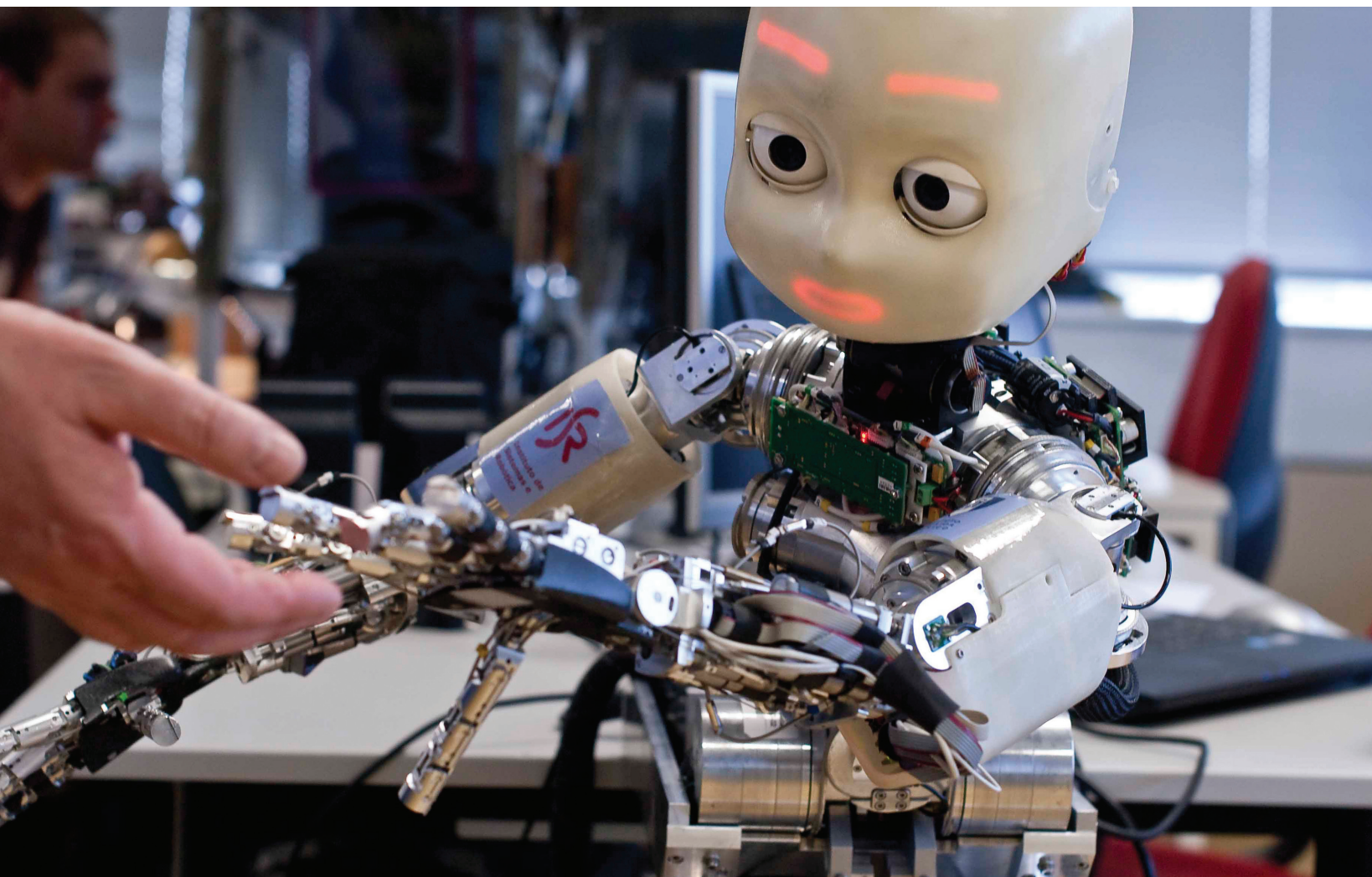
RESEARCH GROUPS

COMPUTER AND ROBOT VISION LAB
(VISLAB)

The VISLAB conducts research in computer and robot vision in a multidisciplinary perspective, combining engineering and computer science as well as fields such as neuroscience, psychology and linguistics. The research is supported by numerous international EU projects and the research team is highly international.

Our research focuses on 3D vision, video surveillance, robot navigation and manipulation, cognitive systems, bio-inspired and humanoid robots. The link with biological systems is two-fold: designing artificial systems inspired after biology and providing models to help understanding natural systems (or how the brain works).

The lab is equipped with cutting edge research infrastructure, including one iCub humanoid robot, a wheeled humanoid platform, cameras and sensor systems and motion/gaze capture systems.

DYNAMICAL SYSTEMS AND OCEAN ROBOTICS GROUP (DSORG)

The key objectives of the DSORG are to meet some of the challenges in advanced robotic vehicle systems design and control and to contribute to the development of cheaper and efficient tools for ocean exploration, bridging the gap between theory and practice. Tools include surface and underwater robots, as well as aerial vehicles working as communication relays or re-directing the operations of marine vehicles.

The group benefits from excellent experimental facilities (laboratories and electrical/mechanical workshops), has access to a set of autonomous marine and air vehicles to carry out field trials, and cooperates with a vast network of international partners from Europe, India, China, USA, and Japan.

INTELLIGENT ROBOTS AND SYSTEMS GROUP
(IRSG)

The research and development work carried out at the Intelligent Robots and Systems group (IRS group) approaches complex systems from a holistic standpoint. The topic of cooperation (among agents and/or robots, among robots and humans) arises naturally from this viewpoint. We use Artificial Intelligence concepts (e.g., sequential decision making, cognitive systems) driven by formal approaches that stem from Systems and Control Theory and from Operations Research (e.g., mathematical modeling, optimization, estimation theory, Markov decision processes). Our research is developed by a team of international post-docs and students, tested in real robots and other complex systems, and carried out in collaborative projects with several international research groups.
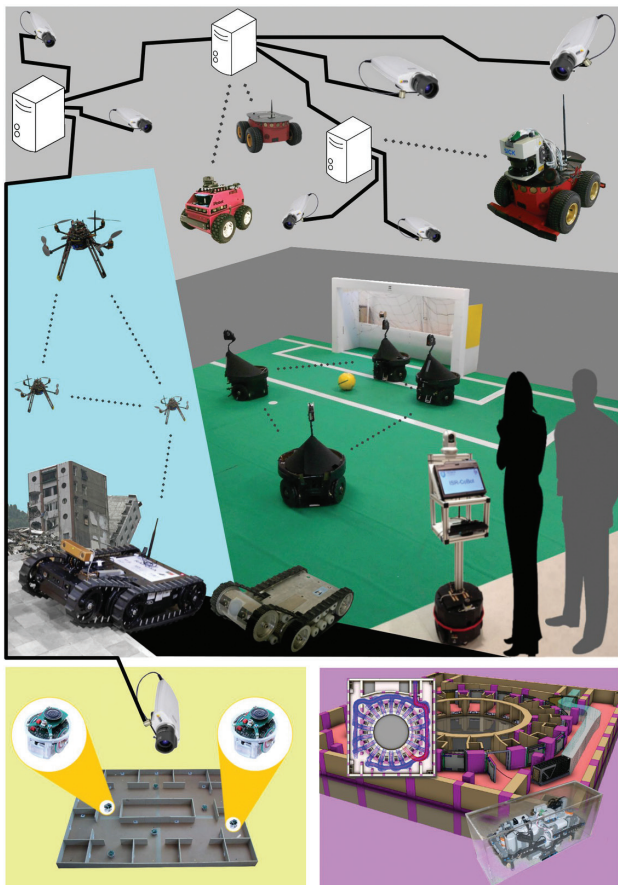
EVOLUTIONARY SYSTEMS AND BIOMEDICAL ENGINEERING LAB (LaSEEB)

The research activities at the Evolutionary Systems and Biomedical Engineering Laboratory (LaSEEB) span two main areas. The first one is in Biomedicine, namely on sleep, cognition and computational neuroscience, from biological signal processing and classification to functional brain imaging, using EEG and fMRI aimed at the identification of biomarkers or diagnosis and monitoring of neuropsychiatric disorders. The other area is bio-inspired optimization, from evolutionary computing to swarm intelligence and agent-based modeling, and simulations of bio-systems. Besides Medicine, our research and development work has been applied to Biology, Agriculture, Energy and Operational Research topics.
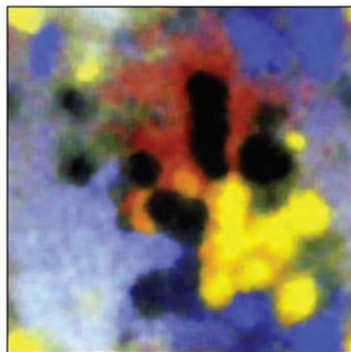
SIGNAL AND IMAGE PROCESSING GROUP (SIPG)

Research at the Signal and Image Processing Group (SIPG) is organized along five areas: a horizontal area that deals with innovative mathematical tools to address problems in signal and image processing, and four other areas that feed on it and build the path to more application-driven research (Sensor Networks, Underwater Acoustics, Image and Video Analysis, and Biomedical Engineering).

Topics of interest include: inference and optimization methods for non-Euclidean spaces; decentralized estimation, detection, and optimization algorithms; 3D object reconstruction from video; object tracking and human activity recognition; ultrasound and magnetic resonance image processing; acoustic methods for underwater communication and environmental assessment.
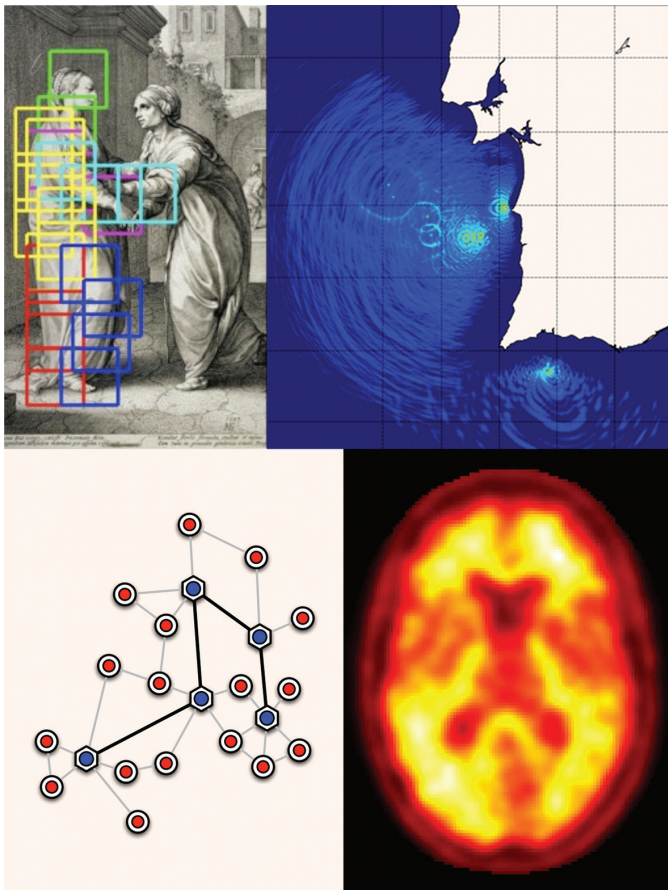
TECHNOLOGY TRANSFER

> **ISR-Lisbon has nurtured partnerships with startup companies that were spun off from R&D activities developed by former students who became technological entrepreneurs.**

ISR-Lisbon has nurtured partnerships with startup companies that were spun off from R&D activities developed by former students who became technological entrepreneurs.

IDMind was ISR-Lisbon first spinoff. Established in 2000, this SME focuses on robotics, mechatronics and system integration. Its portfolio includes the search and rescue robot RAPOSA, the SIGA robots for the headquarters of Madrid's Banco Santander and the FROG robot assistant for tourists.

In the same year, Reverse Engineering began its activity with an optic three-dimensional scanning system resulting from the research conducted by the two founders at ISR-Lisbon/ IST during their PhD. The company diversified its portfolio to include assembly line quality control systems for dimensional or color-based control, tools for deformation analysis, digitization systems for the shoe sole industry (mold alignment, reverse engineering), digitization systems for medical and biometrical applications, digitization services and user-friendly systems for 3D multimedia. Its product Fishmetrics won the 2008 BES Innovation Award.

Observit was founded in 2001 to develop products for video surveillance. It has developed and installed several video surveillance systems for Portugal Telecom headquarters, Banco de Portugal (Carregado), Portuguese Air Force facilities, Brisa highways toll charge systems, and Dolce Vita Tejo shopping center (including facial and automobile plate recognition systems). It has collaborated with ISR-Lisbon on EU-FP7, CMU-Portugal and QREN funded projects.

Blue Edge started in 2003. Its activities focus on marine robotics, data acquisition systems, sea operations including high-resolution sonar bathymetry, and ROV inspection systems. The company was involved on a privately funded project on wave energy exploitation, and on the EU FP7 project CORFAT. Currently, the company is involved in an offshore test station within the EU KIC Innoenergy project of the European Institute of Technology.

Albatroz Engenharia started in 2006 as a follow-up of a project of the EDP-group company LABELEC in collaboration with ISR-Lisbon. Its main development lines are on LiDAR and video signal processing (e.g., for mapping and power line inspection), aeronautic systems and hardware integration. It has developed a power line maintenance inspection system based on LiDAR that has already been in use for 5 years to inspect 105 000 km of power lines in Portugal, Spain and France.

SelfTech is the youngest of ISR-Lisbon spinoffs. It was founded in 2008 and received several awards since then, the most prominent of all being the 1st prize in a Call for Startups of the INNOROBO 2013 event, the largest European exhibition on service robotics. It is involved in the EU FP7 MOnarCH project with ISR-Lisbon, and its main product is the Golmow lawnmower robot for golf courses.

ISR-Lisbon was part of national consortia involving Portuguese companies in areas such as highways toll systems, search and rescue robots, inspection of critical infrastructures, environment monitoring by sensor networks, and public health institutions.

SOCIETY OUTREACH

> **Robotics has been used to motivate young people to pursue studies and careers in science and technology, as well as to demonstrate the usefulness of research to society. Hundreds of high school students visit ISR-Lisbon labs every year and a selection of them participates in summer projects regularly organized.**
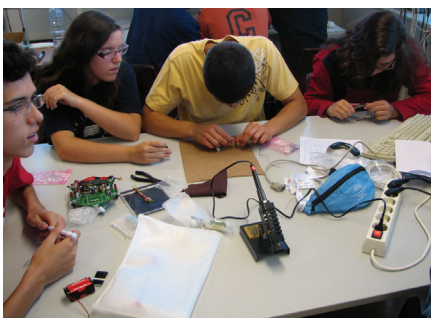

ISR-Lisbon has a distinctive and long lasting experience of outreach activities. Robotics has been used to motivate young people to pursue studies and careers in science and technology, as well as to demonstrate the usefulness of research to society. Hundreds of high school students visit ISR-Lisbon labs every year and a selection of them participates in summer projects regularly organized. ISR-Lisbon has been at the forefront of a plethora of *Ciência Viva* (Science Alive) projects and activities since the early days of the agency:

· The RODITAS project, through a partnership with the technical school INETE, was the first *Ciência Viva* project on robotics and lasted from 1998 until 2002. It started as an extra-curricular activity but the development of the different modules of the robot ended up being part of the student courses.

· The *Ocupação Científica de Jovens nas Férias* summer activities, conducted yearly since 2000, have brought to ISR-Lisbon approximately 300 boys and girls from the 10th till the 12th school years, to build and program from scratch a small robot in one week. In 2007 and 2008, the activities were extended to IST´s Electrical and Computer Engineering Department.
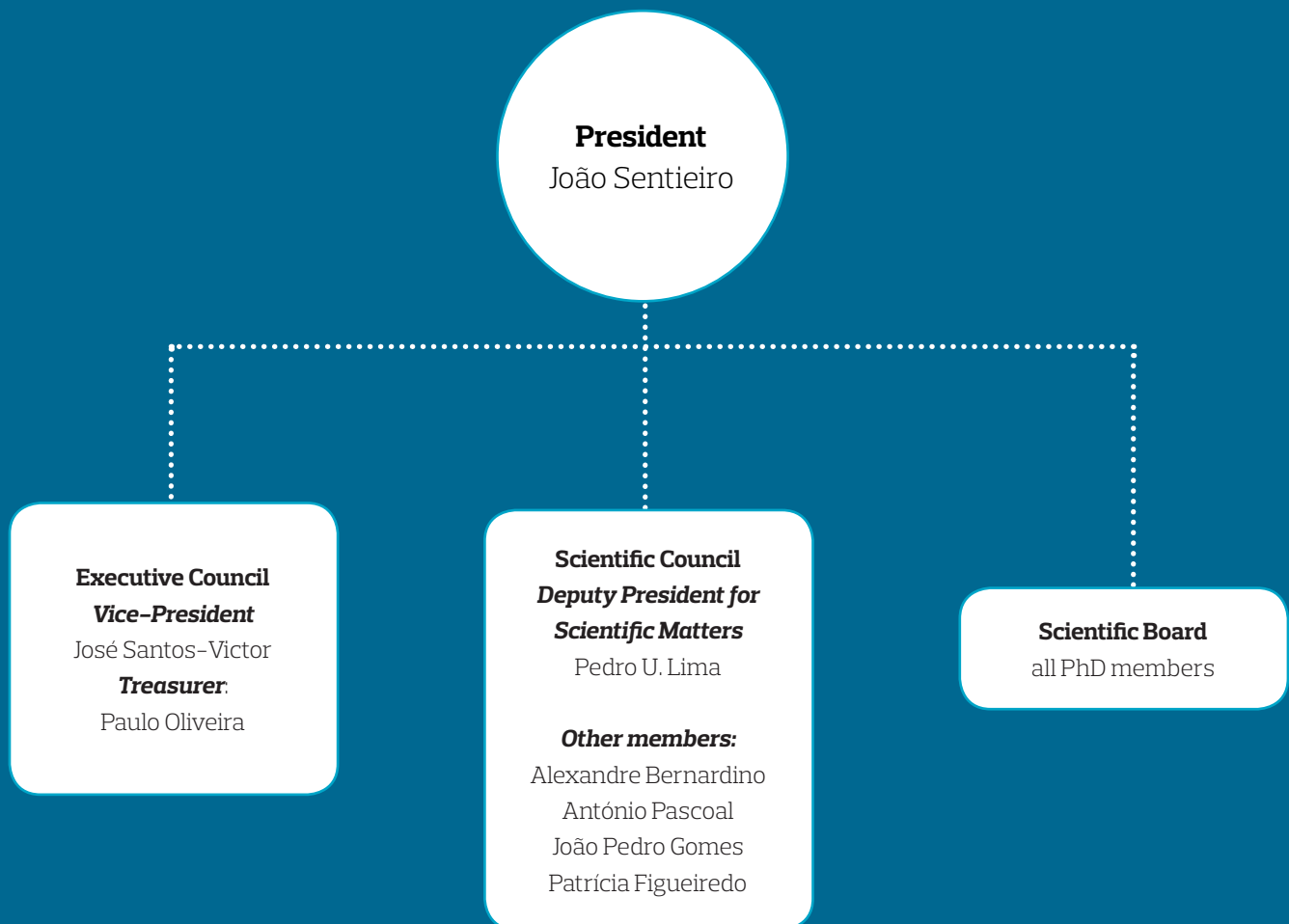
Outreach activities are not limited to educational programs. ISR-Lisbon members have been key players in national activities in Robotics, namely as founders of the Portuguese Robotics Society in 2006, active participants and organizers of the Portuguese Robotics Open since 2001 (two editions in Lisbon were co-organized by ISR-Lisbon in 2003 and 2011) and of RoboCup 2004.

FACTS AND FIGURES

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Founded in 1992
Located in the North Tower of IST Alameda Campus

PhD Researchers:
·   Faculty (IST): 26
·   Faculty (U. Algarve): 5
·   Post-Docs: 12

Staff: 7

PhD student grantees: 83 (28 foreign)
MSc thesis students and project grantees: 75

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