Advanced Adaptive Control for Outdoor Mobile Robotic Systems Facing Unstructured Environments: Application to Humanitarian Demining

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1. Introduction.

More and more research activities focus on the design and the control of mobile robotics systems. Through several workshops and work-meetings organised under the IARP and the European Clawar Network, requirements related to the both aspects have been examined and developed prototypes have been compared. The design strongly depends on the application: indoor or outdoor, in a structured area or in a unstructured, sometimes unknown, environment, with or without manipulating tasks, etc The control, also imposed by the kind of application, belongs to one of the next categories: tele-operation, supervisory control, autonomous control and cooperative control. We only focus on unstructured environments

1.1. Design [1]

One of he most important aspect s of the design lies in the choice of the mechanical structure and the nature of the locomotion and the actuation. The design directly impacts the control.

Wheeled Robots: There are a huge number of examples of wheeled mobile robots developed in the last decades. In the category of robots designed for the detection of mines, for instance,belong robots such as GRYPHON (Tokyo Institute of Technology), the Mine hunter Vehicle (MHV- Chiba University), TRIDEM (RMA, Belgium).
Flying: Unmanned Aerial Vehicle (UAV) is a research field with a great interest both for commercial and for military applications. There are many different kinds of vehicles designed and many research groups are working to build completely autonomous vehicles able to reach a given location without tele-operation.
Hybrid: Hybrid robots are machines that integrate both wheels and legs in order to obtain a compromise between the capabilities of legged machines (adaptability to very rough terrain) and wheeled machines (speed, autonomy, stability). Among the examples of such kind of robots is the HYLOS (LRP, France) with four wheels, each one mounted at the end of a leg.
Legged: These can be grouped in many ways, such as application, type of actuation or number of legs. Biped research has received considerable interest and Japan has a major R&D programme where the aim is to produce a human-friendly system that can interact with humans in their everyday environments. There are numerous examples of four-legged systems and Germany has a major R&D programme in this area. The most advanced four-legged system that has been developed to date is probably Sony's pet robot, AIBO. A number of six-legged robots have been developed using ideas from nature, such as insects, and have incorporated a number of sensors and neural control methodologies. These include AMRU-5 (RMA, Belgium), MECANT (Helsinki University of Technology, Finland), SILO6 (CSIC-IAI, Spain), and many others. Several eight-legged machines have been developed based again on biological thinking, such as spiders and crabs.As an example, a eight-legged pipe climbing robot has been developed by Neubauer of Siemens AG, Munich.

Fig 1. The AMRU-3 electro-hydraulical driven six-legged robot

Tracked: Tracked machines have had a long history in comparison to legged machines and many machines have been commercialised. For example, the HOBO tracked vehicles produced by Kentree have been used for anti-terrorist measures in over 30 countries. In addition, there are a variety of commercial civil or military vehicles with tracks, including armoured vehicles, tanks, bull dozers, etc.

1.2. Control

The use of UGVs or Unmanned Ground Vehicles for difficult tasks in unstructured environments may not be expected before a few years [2]:
- first because a specific mission often implies the use of several vehicles of different types (as an example, a De-mining mission entrusted to robots should have to combine a vegetation-cutter to prepare the scanning of the minefield, a Sensor-carrier for the detection of UXO, a mine-clearer for the removal or destruction or the neutralisation of the detected explosive device, etc)
- secondly because the control/command/coordination or C3 decisions never belong to one operator but to a hierarchical organisation (That's typically the case for military applications)
- last but not least, because those UGV have to continuously face unexpected and dangerous environmental changes implying:
(a) an adapted (to the mission) design of the vehicles
(b) a high-performance dynamical control of these systems,
(c) a fast and reliable processing of data gathered by a lot of on/off-board sensors
(d) safe and reliable communications.

The adaptative (tele-) control self implies the use of teleoperation, telepresence and distributed intelligence: the teleoperation is the extension of a person's sensing and manipulating capability to a remote location implying communication channels from and to the human operator; the telepresence defines the techniques allowing the human operator to feel himself physically present at the remote site; the intelligence combines the sensory processing, the world modelling, the behaviour generation and the value judgement to perform a variety of tasks under a-priori unknown conditions. Combination of teleoperation, telepresence and human-machine distributed intelligence often defines the supervisory control. Through the introduction of AI techniques and use of the virtual reality, the roboticians try today to develop the concept of adaptative autonomy and virtual symbiosis as explained by the next table which is based on the five stages introduced by L.A.Peterson [12] we have met at the Human Engineering Laboratory (HEL) during the NATO/Panel 8/RSG 18 activities , completed with some still needed R&D to be encouraged.

Stage	Characteristics	Example	Needed HMI R&D
1980/90 Bounded Autonomy	Structured environment	Industrial robots or GUV (Guided unmanned vehicles)	Fixed Pre-programming No specific R&D needs
1990/95 Teleoperation	Full time presence of	Space Applications	Video-Audio-Tactile

	the Human Operator(s) in the loop	Military Applications Demining	processing (Sensory), Real-time World Modelling, Ergonomy
1995/>2000 Supervised Autonomy	Distributed Intelligence (Control Station/Vehicle)	Space Application (March Rover) Military applications Demining	Safety and reliability of Communications to/from UGVs, High/low Level Control and Command
>2000 Adaptative Autonomy	Learning capabilities	Indoor Prototypes Legged robots (Honda P3, AMRU-5,etc)	Adaptive Processing Techniques (Neuronal, Genetic, Fuzzy Logic,..)
> 2000 Virtual Symbiosis	Co-working capabilities	Multi-robot-cooperation	Multi-agent-cooperation (+ UAV/UGV combinations) Prototypes Virtual Reality, a.o.

Table 1. From the easiest controller (PLC) to the most recent adaptive controllers

2. Risky Interventions

Currently, the use of unmanned systems as a method of data and information gathering for use in Civil (and Military) Security is an under-utilised resource. Among the most concerned missions that could be partially entrusted to mobile Robotics Systems inserted in a network of fixed and mobile Sensors Systems, let us mention the interventions in prevention , during or after a natural (inundation, earthquake, volcanic eruption, forest fire) or artificial (dissemination of explosive devices, minefields, terrorist action's consequences, accidents) disaster. Among the reasons why this resource is under-utilised, one may mention, beside the reasons we underlined in the previous paragraph, the immaturity of some technologies , the lack of confidence in the reasoning and reaction capabilities of unmanned vehicles and the bespoke nature of the robots self: these are often defined for a specific purpose and generally have a single role and a single command source. Each bespoke system will have its own Command and Control station and its own Command and Control architecture and protocol, usually a specifically designed control station and its own data processing capability tuned to its design requirements [3]. As an example, about 30 robots have been designed over the world for helping the automated detection of anti-personnel mines in infested Countries: all different and hardly compatible…
However, the use of unmanned vehicles offers civil authorities the capability to monitor and gather data from a large risky area with minimal manpower. Acceptance of unmanned vehicles within area of operation by civil authorities will become more acceptable, depending upon the type of vehicle and the nature of the need for the vehicle, if the cost-effectiveness and the modularity-interoperability of the platform are increased as well as the reliability of the sensors allowing their optimal (intelligent) control and the success of the mission entrusted to them.
Let us now examine the above mentioned design and control aspects for such interventions

2.1. Robotics Platforms.

The first and still intensively used robotics platforms belong to the Defence and Civil Protection Units and an important market seems to grow, influenced by unstable political World evolution, the increasing number of local armed conflicts, terrorist actions, accidental explosions of polluting industrial sites, etc
Tracked vehicles are presently employed as the most suitable for negotiating obstacles of man-made and natural topographical nature. In order to have a combined vehicle with track system and climbing ability, the vehicles weight is normally kept to a minimum. The concept of a light tracked machine has been employed for use in the remotely operated vehicle (ROV) industry, an example of this is the Kentree Ltd – BRAT product (See Fig 1). The Brat vehicle is a relatively lightweight ROV with rugged terrain and stair climbing ability.

Fig 2. Kentree Ltd BRAT and HOBO vehicles

Wheeled vehicles have huge advantages over tracked machines because of their simple rugged drive system in comparison with track systems which required an amount of maintenance. Utilizing optimum design techniques of load distribution over driving wheels, a wheeled vehicle can be employed to surmount rugged terrain. The Kentree Ltd large wheeled product – HOBO, has the ability to surmount rugged natural terrain and man-made structures such as steps, stairs and dykes, see Fig2.

Beside this existing market, two new markets seem to raise, the market of the multi-legged platforms and the market of the UAVs, the first one to face the mobility difficulties on very unstructured terrains (woody and mountain areas, for instance), the second one to monitor large areas and develop suitability maps by natural or artificial disasters.

There are several reasons explaining the use of legged platforms [1]:

- Walking machines need only some foothold an therefore are more flexible then wheel-driven machines. This is very important because of the huge amount of obstacles which could appear in these areas.
- In disaster areas in which e.g. house or other construction are caved in, it is very important to have a light weight machine.
- The adaptation to the ground and the control of the body on smooth trajectories is necessary if e.g. special kind of inspection sensors are carried with the machine.

Up to now there are only a few prototype machines, which were especially build for the use in disaster areas. The main reason for that is that the perception of the operational environment in real time is still an open question. Also the control of locomotion has to be solved completely for getting full autonomy in rough terrain. The next pictures illustrate the capabilities of the German FZI – LAURON III robot.

Fig 3. FZI – LAURON III

A second category of mobile robotics systems appears on the R&D market, since the Entry into force, in 1999, of the OTTAWA Treaty adopted on September 1997, the Convention on the Prohibition of the use, stockpiling, production and transfer of AP-mines and their destruction, the robots for detecting, neutralising, removing and/or destroying the anti-personnel mines and/or explosive devices infesting a lot of countries affected by civilian wars and local conflicts. Several designs , depending on the nature of the minefields, have been proposed, as illustrated by the next examples:

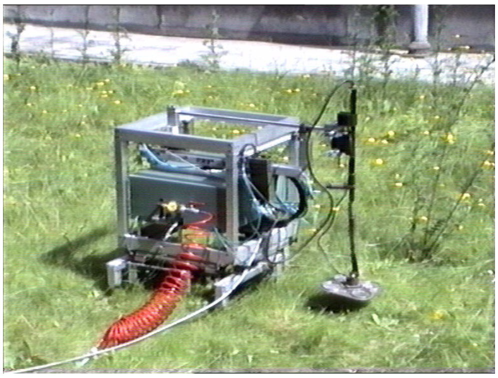

Fig.4. AMRU-4, sliding robot (RMA,BEL)

Fig 5. THRASHER, wheeled mine-clearer (KentreeLtd, IR)

Fig 6. ARES (New University of Lisbon, POR)

Fig.7. GRYPHON IV (Tokyo Institute of Technology, JPN)

The environment play here a large part in determining the attributes or characteristics of the UGV equipment. In fact it is unlikely that a multi-purpose, single machine will be developed that will cope with all forms of environment. The environmental issues fall into various categories and equipment operation will need to be defined as desirable or mandatory under these conditions. Main environmental characteristics that need to be taken into account are:

- Weather eg temperature, snow, ice, frost, rain, wind, humidity .
- Terrain eg urban - street, inside buildings; rural - desert, rocky, heavy vegetation, possible water scenarios.

Payload assessment must take into account two factors, expectations based on current engineering capability and those desired for the future, although the latter may be quite impractical at the present time. However, from knowledge of the various sensor systems being considered (Metal detector, Ground Penetrating radars) , a payload in the range 5-15kg is likely.
Various mechanism types are being considered. There is , in particular, taking into account with the nature of the infested areas (about 50% very unstructured areas) a need to concentrate on scenarios where tracked and wheeled vehicles will be unable to carry out the de-mining task. The likely configuration will therefore be a light-weight, articulated legged walker (CLAWAR) able to clamber over rough terrain, cross ditches, walk

through heavy vegetation without disturbing it and hidden trip wires, climb steep slopes, etc. It will also have sufficient degrees of freedom of its body with respect to its legs to deliver sensor work packages and marking devices, probably on a boom or manipulator to difficult to access positions, accurately.

The actuation method is unclear. Electric motor driven joints seems the most likely although pneumatics and/or hydraulics should not be ruled out. Either way, the power requirements of the vehicle are likely to exceed significantly those of the work package. Use of an umbilical, although possible, will seriously degrade the operational scope of the vehicle so suitable on-board power devices may be required. The weight of battery packs or motors for producing compressed air is significant and a balance between functionality and mission length may be hard to achieve. Soft pneumatic muscle actuators may provide some solution since, weight-for-weight, they are able to provide much higher power for lower pressure than pneumatic cylinders. In the short term, the use of an umbilical may be necessary whilst suitable on-board power technology is found.

Motion control will need to be highly sophisticated. General motion in difficult terrain will need advanced adaptive gait control such as is being developed at present in various research centres. Closely controlled motion will be required to deliver sensor packages to accurate positions when detection is in progress.

The motion of the vehicle will demand by far the highest power requirements. Whilst some scenarios will allow the use of an umbilical, many will need more autonomy so an on-board power supply will be needed. Thus efficiency of motion will be most important, requiring advanced control algorithms. On the other hand, speed is unlikely to be paramount since detection will take time and will probably limit forward motion.

The modes of operation need to be specified. Most requirements will have a man-in-the-loop operation and there will be a direct line of sight operation at a safe distance. This safe distance will have to be specified and as will the method of ensuring that the safety restraints are carried out correctly. Typically, current methods for remote control from close in up to 1-2 km distance use tele-operation.

Examples of the advantages of tele-operation are that the task can be carried out by a single operator and that camera positions are easily selectable using a microwave link or fibre-optic for a line of sight video transmission from the CLAWAR machine to the remote command station. To carry out complex tasks, the numbers of cameras needed and their positions will have to be considered. It is likely that at least two fixed or one rotational camera will need to be fitted to the vehicle to give all round viewing during operation. Operator control units can be fitted to display single or multi-image options. The communication link might be a 1.4 GHz video link . Fibre optic links that offer high bandwidth can be used but the trailing of cables can be a problem over long distances. A communications link to carry control and sensor feedback signals will also be required, probably using a fibre optic link.

In summary, machines to carry out demining activities in place of human deminers are generally likely to be wheeled or tracked. However, there is a possibility that in certain terrain, walkers will add value. There is little likelihood that pure climbers will be required. Assuming that the friction of its feet to the ground is sufficient to provide the traction required, then provided the vehicle has the motive power to operate on steep inclines by modification of its gait, then a walker is sufficient. Such machines are likely to be light in weight. The control and communications system is likely to be of a nature which will facilitate the addition of higher order functionality such as sensor fusion, HMI, navigation, etc.

The walker will need to carry several Kg of work packages; a selection from vision cameras, IR cameras, GPR, UWBR, metal detectors, chemical sensors and other more advanced detectors. Some may need to be held on a boom arm or manipulator. The machine will need to be able to traverse rough ground without operator intervention so a high degree of gait "intelligence" is required. Since ground conditions will vary considerably within mission, it will need to be able to sense ground condition and adjust its gait in-mission. It will need to be able to hold detectors in a pre-determined relationship to the ground contour and to control delicate prodding movements.

The complete system will need to integrate the vehicle control and navigation systems with a data fusion system that will discriminate, to a high degree of confidence, between mine and 'no-mine' conditions.

Some such machines may need to be specified so that they can operate fully submerged in shallow seawater. Clearly, the choice of the sensors systems, the design of the mobile platform and the efficiency of the Human-Machine-Interface play an important role in the development of the controllers that will have to be used.

2.2. Control

Referring to the table 1, several controls may be envisaged for dangerous tasks.

2.2.1. Tele-operation

The EOD (with manipulative tasks) , RSTA (Reconnaissance, Surveillance and Target Acquisition) missions, in their simplest conception, may be entrusted to Tele-operated vehicles with, at least, the next sensory: cameras , acoustic sensors, laser range-finder, FLIR, Cameras (without taking into consideration with the proprioceptive sensors allowing the dynamical control of the UGV)

The main source of information to the operator and the most difficult reliable/convivial interface to develop is, in the static or mobile (following) Control Station (CS), one or more monoscopic video displays or stereoscopic displays and their attributes as well as the optimal positioning of the sensor(s) on the UGV and the possible use of Helmet Mounted Displays in the CS. No other methodology than the Ergonomics study, beside the accurate knowledge of the mission requirements, may help to choose the 'best' solution. The system must generate the confidence of the Human Operator thanks to fast perception of the scene, enhanced detection of slopes and depressions, enhanced object recognition , detection and possibly manipulations, enhanced performance with fewer errors under various operating conditions. As an example, let us consider the experiences of the DCIEM (1993 : Defence and Civil Institute of Environmental Medicine [13]) and the more recent trials of the HUT (Helsinki University of Technology, [4]1999, both based on outdoor motions of a unmanned EOD-like wheeled vehicle, both considering , a.o., manipulating tasks, both testing experienced and less experienced operators. Two general and still valuable conditions of proper evaluation have been underlined by DCIEM : (a) the people behave in a regular, repeatable and logical way in the laboratory but not in a field environment where unpredictable events impose un-codified reactions and (b) an experimenter may not attempt to use laboratory techniques in field situations. In the both cases, advantages and drawbacks have been underlined as well for the monovision as for the stereovision, with nevertheless a preference for the last one in case a high accuracy and a good evaluation of the distance are necessary. The HUT study also focused on the tele-presence and concluded that the Head-Tracking offered to the operator working in the CS a better support to face the unknown changing situations. The last study also suggests to take into account with the other senses of the HO and certainly the sound.

For RSTA missions, the techniques of (aerial/ground) target detections and tracking within the field of view (FOV) also require the use of vision systems and the development of intelligent predictive acquisition/recognition models. In our laboratory we developed a reliable method for colour object detection, based on the object's Hue and a predictive Kalman filter tracking algorithm [5] : a coloured target is putted on the top of a mobile robot and tracked by a colour camera (figure 8) : real-time tracking indoor experiences on unmanned vehicles moving at 0.6 m/s gave the expected resolution of 1 cm over a maximal distance of 30 m, but same outdoor experiences first failed due to the continuously change of the reflection properties of the target resulting from random change of motion direction under variable illumination conditions, then succeeded with a lower resolution (30cm over the same distance)

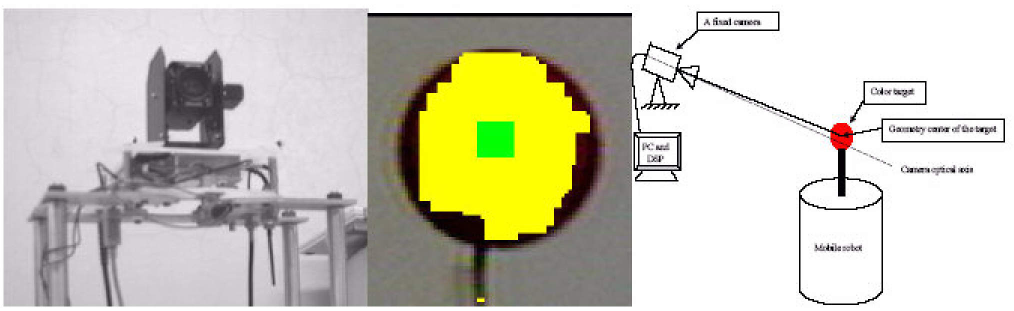

Fig.8. Hue-Colour-Tracking (RMA, BEL)

The next table summarises the excellent conclusions of K.P..Holzhausen [6] concerning the R&D needs of the classic Teleoperation techniques :

Vehicle control	Design of the Control Station (number of operators, screens, type of feedback signals, type of command devices such as keyboards, joysticks, computing capabilities and modes , Design of the Vehicle (related to the type of mission , the environmental conditions, etc.)
Camera control	Camera position and orientation (depth perception, bird's view), remote control of the cameras, stabilisation, zoom control)
Enhanced Depth Displays	Stereo versus Monovision, graphical overlays, FLIR visualisation, Combined Sensor visualisation (position of the vehicles as well as application-related signals)

Video Overlays	Vehicle subsystems informtions (speed,attitude),- topography information, alarm informations (unexpected events) Communication link status., all non model based informations which may not lead the operators to lose track of the primary display process
Exocentric Information	Display of the TOV in its environment through Telepresence techniques, Map information

Table 2. Parameters to be designed for a correct Tele-operation

Studies on the optimal use of mono/stereo/B&W/colour cameras and other visions systems continue and will lead to very performance classic Tele-operation techniques : combinations of vision systems (CCD, Laser, IR, US..) also have to be applied for allowing the simultaneous functions related to the mission : driving of the vehicle, tracking of the target, manipulating of objects,…. : data-fusion algorithms, multi-screen visualisation, cooperation of Human operators in the same Control Station are problems which may be solved at near term but which still need a lot of tests under realistic simulated on-the-field constraints. Extrapolating the recommendations of H. Winter [14], the following rules and considerations have to be used in the design of control stations: - Anticipation assistance is preferred to reactive actions

- Assistance must be homogeneous and produce constant understanding interpretation model
- Assistance must know and respects its own limits
- Dialog must be adapted to context and workload
- Assistance must be adapted to the user's skills

2.2.2. Supervised Autonomy

As previously said, if some ‘military’ EOD, RSTA and/or Combat Support tasks may be enntrusted to teleoperated vehicles, the most missions impose a supervisory control in which the Human Operator(s) act as supervisor of actions performed automously by the UGV and not as responsible for all control inputs : such distributed control allows a knowledge based mission/task planning and, consequently, implies R&D in AI (Artificial Intelligence : cognitive processings have to be implemented onboard of the UGV and in the Control Station(s)).

Let us consider the example of Humanitarian Demining whereto Robotics Systems could be used [3]:

An optimal approach should consist into providing a supervised autonomous UGV that can remove excess vegetation and then deploy a multi-sensing detector with sufficient precision to provide a reliable mapping system of detected mines. This will involve a combination of several different sensors, including:

- a sensor to determine the location of the robot vehicle within the area to be cleared
- an explosives proximity sensor to enable safe navigation
- a multi-sensing mine detector, incorporating for instance a 3D metal detector and a GPR
- a sensor to determine the position and orientation of the multi-sensing detector.
- sensors to control the attitude of the vehicle
- a vision sensory to allow the supervised autonomy (HO in the loop)

The architecture of the system could be the next one :

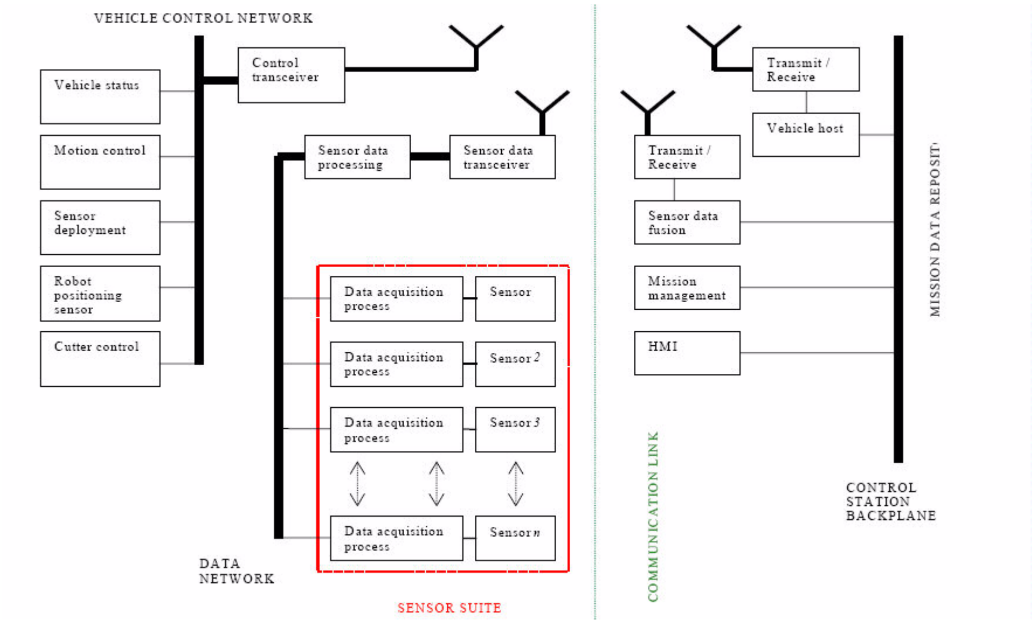

Fig.8. Modular Control of a de-mining Robotics System (RMA, BEL)

The most supervised autonomous systems work on a top-down approach (on the figure, from the right to the left):

Control Station (Top) :

This TD approach is the best approach if we consider that the Application related Control and Command has to implement three primary activities, defined in the block 'Mission Management : (a) the planning process including the valuation of the environmental conditions compared to the available data (for instance, primary map of the minefield from an aerial detection, with some information on natural relief, obstacles, ..) in order to generate a series of tasks (path-planning, cutting of the vegetation, inspection mode – choice of the sensor, sensor deployment -....), (b) the directing process which defines with a high precision and on unambiguous way the operations (a set of operations or sub-tasks defines a task) that will be controlled by the Human Operator(s) and (c) the monitoring process involving the Tele-operation aspects we described in the previous paragraph. The intelligence of the system lies essentially in the first two processes : an Expert-System (ES) will assist the mission manager (and, indirectly the HO during the monitoring process). Such an ES includes a comprehensive database (GIS, Geological information, Mines and UXO information/description, characteristics of the UGV, of the Sensors, etc), a set of rules and a strategy allowing the best choice of rules according to the objective (minefield delineation, precise scanning of well-defined area, etc). The monitoring process imposes a correct design of the HMI (see previous table 2)

UGV (Down) :

In the supervised mode, the safety and the performances of the communication (particularly non-line-of-sight) as well as the computing speed capabilities of the Informatics systems play a major role : a considerable literature (a.o. for military Ground missions) describes the constraints related to those factors : example : standard 19.2 Kbit/s (need of compression for the High-Bandwidth, typically 20 MHz for one vehicle in frequency modulation mode, Video signals).
The vehicle control network and the data network impose the development of High Level - Low Level control software : here also a considerable literature suggests solutions : as an example, the ANCEAEUS control system [7] adopted on the JINGOSS mine-detection system developed by the Canadian Forces (DRES Defence Research Establishment Suffield) and mounted on a 8x8 wheeled vehicle ARGO (used in Somalia) : the Vehicle Superviser includes its own navigation module (semi-autonomous navigation, vehicle status monitoring, DGPS positioning functions,..) and its own application module (detection/marking).
The objective of the Supervised control is clear: to free the human operator(s) to concentrate on a higher level of control and optimally achieve the planned mission. No any supervised control may be successfully implemented without having satisfied to the next requirements: (a) the use of a UGV adapted for the mission (mechanical structure, locomotion, actuation, sensory, etc.), (b) the training of the human operators (all ranks, thus including the Commando levels through an appropriate series of courses on the emerging information and control

technologies) thanks to on-the-field simulations, then on-the-(dummy mine/dummy battle -) field trials under varying environmental conditions including uncertainties or randomly occuring events, (c) the funding of R&D activities related to the four issues that were, a.o., underlined in [3] :

Optimal allocation of information processing (interactive planning and control at the mission level, timely reactions on observed deviations)

Optimal allocation of control functions (High Level/Low Level motion control of the UGV and orientation/positioning control of its sensors)

Multi-Vehicle Control (Integration of navigation, task, sensory modules under predictable structured conditions, - Idem under Uncertainties)

The first R&D results related to the last issue , in real-time outdoor conditions, are still stammering.

2.2.3. Adaptive Autonomy

Before a UGV will behave without permanent supervision of human operators, the most high-level actions/functions entrusted to the Human Operator will have to be transferred to the Informatics system equipping the vehicle.

A high-level computer's behaviour must be a model of the Human 'intelligent behaviour : assuming the intelligence may be defined…Albus [7] defined intelligence as that which produces successful behaviour and he identified the factors of the intelligence as (a) sensory processing (b) world modeling (c) behaviour generation (d) value judgment. The last factor, added to the first three ones, will lead to the emergent class of cooperative robots working in harmonious symbiosis with the Human beings. But the first three factors monopolize today the major part of the R&D funds allocated to the Information Technology.

Sensory Processing

A first paradigm asserts that an intelligent robot should be able to perform a variety of tasks under a-priori unknown conditions : as a consequence, the first problem to solve lies in the intelligent connection 'perception-to-action'

: therefore a considerable lot of developments of image processing techniques and data fusion algorithms (because the perception includes all the senses) which are based on assumptions explaining our own intelligent behaviour and derived techniques : neural networks (pattern recognition, tracking techniques, bottom-up learning techniques for walking machines, etc.), fuzzy logic control (navigation, obstacle avoidance, fuzzy control of Coordinate Measurement Machines or manipulative tasks, etc.), genetic algorithms (Pattern recognition, Advisory systems for diagnostic problems or fault detections, etc.).

World Modelling

The perception leads to intelligent actions if the interpretation of the perceived image may be supported by a reliable knowledge of the 'World' : the world modelling, with all possible significance of the word 'World' constitutes the second R&D axis towards an integrated intelligent control. The most actual studies focus on the Virtual Reality (VR) and try to offer the Human Operator(s) a so-called virtual aid (for instance through the use of helmet mounted displays). The Virtual and Augmented Reality can improve the perception by giving the operator additional views and/or visual cues superimposed on the image. Our laboratory [8] proposed a control paradigm that we could call "interactive autonomy" which can be seen as a hybrid case of manual and supervisory control as defined by Sheridan [9]. The basic idea was to provide the operator with virtual views of the mobile robot (in this case an indoor mobile robot, the Nomad) and of its environment, and with programmed tools allowing the operator to execute the mission in the virtual world. Spazz3D, a VRML worlds and avatars modelling program had been used for creating the virtual laboratory. Open Inventor Toolkit was used to import and interact with the virtual world. This world is automatically loaded when starting the application. A scene-graph is generated and nodes which have been defined can be retrieved and modified. In this application we can change the robot position and orientation and the different viewpoints. The figure 9 illustrates two parallel and different views of the environment:

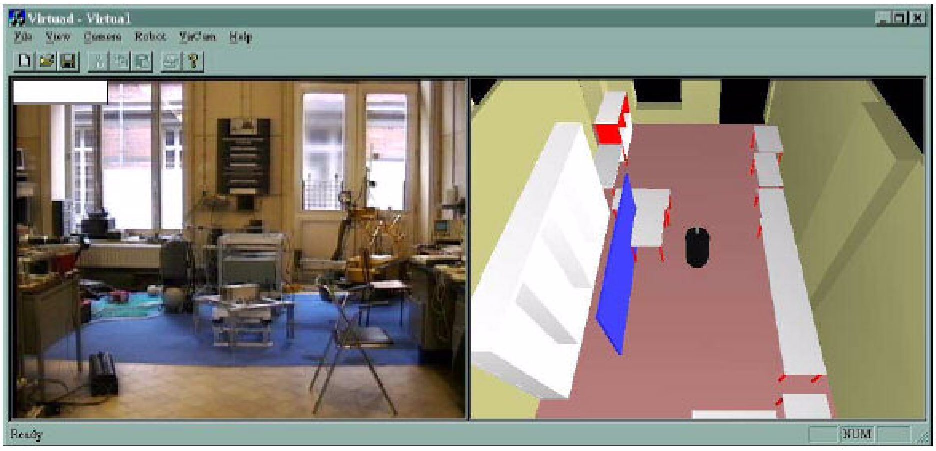

Fig.9. Real and Virtual Bird eye view

The interactive autonomy imposes several constraints : a regular calibration for synchronising the motion of the robot in the Virtual World (tool of the Human Supervisor) and the motion of the real robot in the real world, the choice of the best view for the best control, and the optimal use of all the techniques which have been described under 'supervised autonomy'. The use of such techniques in an outdoor unstructured environment is no more utopian,

and recent IARP workshops [17] enhanced the use of virtual maps to help the operators in charge of the interpretation of the signals and of the final decision related to the motion of the robot and/or of its manipulators, as illustrated by the next figure

Fig. 10. Mapping of the ground and modelling for the generation of the arm motion.

2.2.4. Multi-Robot Control

The more recent projects related to Robotics Systems envisage the cooperation between several robots (individually controlled according to the previous schemes, including possible Human interferences) and actually focus on :

- the Information architecture imposed by cooperative tasks and/or cooperative agents (sensors, actuators, environmental events, Human operator data, manned/unmanned vehicles,etc)
- the behaviour based navigation that introduces a higher flexibility in the control of the robots.

Architecture [10]

Computer systems are the backbones of all robotic applications. Since many years, searchers have developed ad-hoc programs for every new system. It is consequently difficult to build on existing systems and to reuse existing applications. There is a crucial need for reusable libraries, control framework and components. Efforts in this direction have focused on autonomous systems while we are also targetting tele-operation. Some are based on proprietary communication libraries, others are based on CORBA (Common Object Request Broker Architecture). The RMA chose this last base to develop COROBA, a specific multi-robot-control software: such a control has to be based on robust communication libraries and to claim to be open it must subscribe as much as possible to existing standards. When considering communication libraries it appears that one communication middleware has been present for more than 10 years and has now reached its maturity, this middleware is CORBA. Beside the development of the architecture and to improve its capability, a simulator MoRoS3D written in Java already proved the consistency of the chosen middleware. The next figure describes the basic structure of the Robot Control and a view on the treated scene. Tri-dimensional elements have been divided in different categories: robots, obstacles and terrain. Elements geometry can be read from files or directly created using Java code.

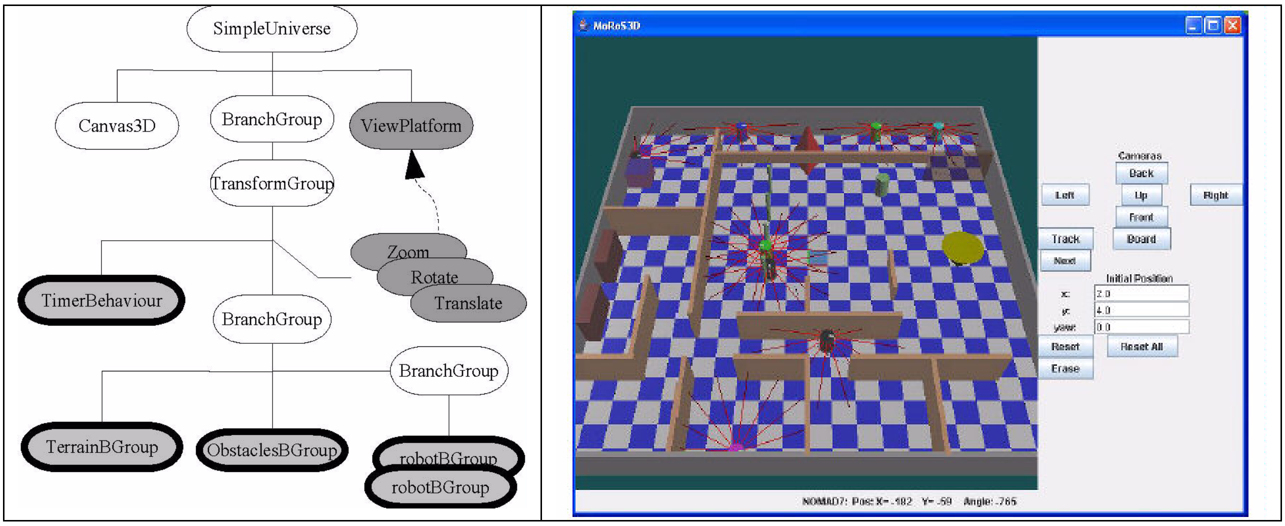

Fig.11. Data structure of the virtual world and virtual world

Behaviour based Navigation [11]

In order for a mobile robot to navigate safely in a complex human-centered environment with multiple dynamic objects, a careful consideration of the robot navigation controller is required. In order to solve this problem, multiple architectures have been proposed in the past.

At one extreme of the agent control spectrum lie traditional top down planner-based or deliberative strategies that typically rely on a centralized world model for verifying sensory information and generating actions , as described under Tele-operation and Supervised Autonomy. The information in the world model is used by the planner to produce the most appropriate sequence of actions for the agent. These approaches allow for explicitly formulating the task and goals of the system, and estimating the quality of the agent's performance. However, uncertainty in sensing and action, and changes in the environment can require frequent (re)planning, the cost of which may be prohibitive for complex systems. Planner-based approaches have been criticized for making real-time reaction to sudden world changes impossible. Various approaches for achieving real -time reaction performance in autonomous agents have been proposed. Purely reactive bottom -up approaches are featured in various implemented systems. They embed the agent's control strategy into a collection of pre-programmed condition/action pairs with minimal internal state. Reactive systems do not maintain internal models. Typically, they apply a simple functional mapping between stimuli and appropriate responses, usually in the form of a look-up table, a set of reactive rules, a simple circuit, a vector field, or a connectionist network. All of those implementations are variations on the same theme of constant -time run-time direct encodings of the appropriate action for each input state. These mappings rely on a direct coupling between sensing and action, and fast feedback from the environment. Purely reactive strategies have proven effective for a variety of problems that can be completely specified at design -time. However, such strategies are inflexible at run-time due to their inability to store information dynamically. Hybrid architectures attempt a compromise between purely reactive and deliberative approaches, usually by employing a reactive system for low -level control and a planner for higher -level decision making. Hybrid systems span a large and diverse body of research. It includes reactive planning or reactive execution used in Reactive Action Packages (RAP), higher -level primitives for planning that hide and take care of the details of execution , Procedural Reasoning System (PRS) , and others. Hybrid solutions tend to separate the control system into two or more communicating but independent parts. In most cases, the low -level reactive process takes care of the immediate safety of the agent, while the higher level uses the planner to select action sequences.

Behaviour -based approaches are an extension of the reactive architectures and also fall between purely reactive and planner -based extremes . Although often conflated in the literature, reactive and behaviour -based systems are fundamentally different. While behaviour -based systems embody some of the properties of reactive systems, and usually contain reactive components, their computation is not limited to look-up and execution of simple functional mappings. Behaviours can be employed to store various forms of state and implement various types of representations. The organizational methodology of behaviour- based systems differs from the classical hierarchical systems in its approach to modularity. The philosophy mandates that behaviour execution not be simply serialized, thus reducing the system to one that could be implemented through more traditional centralized means. The organizational methodology concerns the coordination of a multitude of behaviours, thus making behaviour -arbitration one of the central design challenges of such systems. For the sake of simplicity, in the majority of systems the solution is a built -in, fixed control hierarchy imposing a priority ordering on the behaviours, much like such hierarchies have been used to employ priority schemes over reactive rules, such as for example in the Subsumption Architecture.

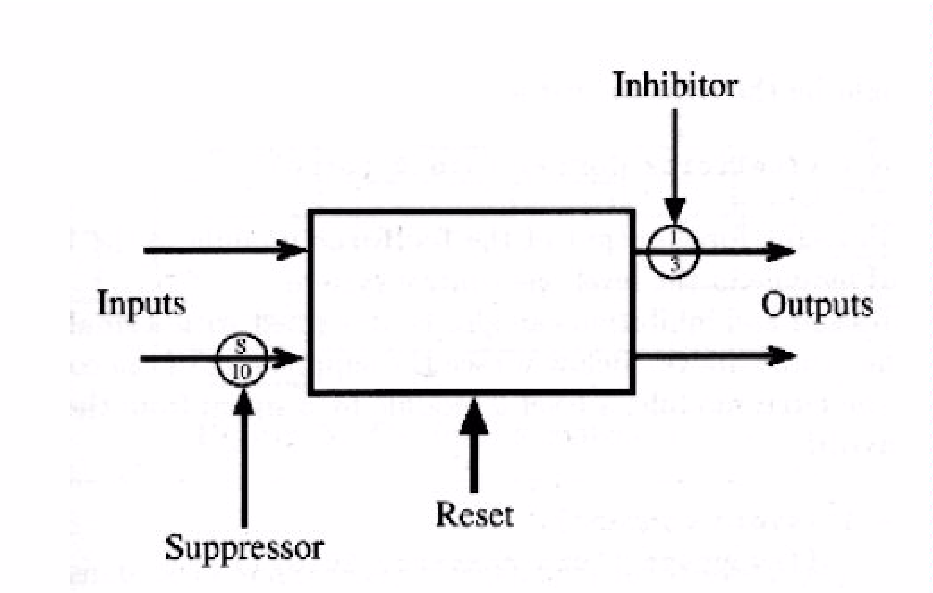

Fig.12. Behavioral module used by Brooks in the subsumption architecture

More flexible, although often less tractable, solutions have been suggested, commonly based on selecting an output behaviour by computing a multi-variable function implicitly encoded in behaviour activation levels, such as voting schemes and spreading of activation. In behaviour -based robot navigation systems, goals are achieved by subdividing the overall task into small independent behaviours that focus on execution of specific subtasks. For example, a behaviour can be constructed which focuses on traversing from a start to a goal location, while another behaviour focuses on obstacle avoidance. In summary, the general constraints on behaviour -based systems roughly mandate that behaviours be relatively simple, incrementally added to the system, that their execution not be serialized, that they be more time -extended than simple atomic actions of the particular agent, and that they interact with other behaviours through the world rather than internally through the system.

The R&D activities of our UGV Centre will now focus on the implementation of behaviour –based navigation techniques into the COROBA architecture.

3. Conclusions.

A lot of studies concludes on the unavoidable emergence of useful Robotics Systems in Risky Interventions and The most studies underline the major impact of the Adaptive Control and the related HMI (Human-Machine-Interface). However, despite of the optimism of the Roboticians and the fact that the end of the 20th century is, in the so-called developed countries, characterized by an increasing automation of several processes (among which some transportation or mobility applications) thanks to the advanced technologies based upon the electronics and the nascent biomechanics, micro- and nanotechnologies, the systematic use of UGV or Tele-operated Land Vehicles for outdoor/indoor Risky applications may not be expected before a few years: but fast progresses indicate that the Robotics becomes a mature technology: mobile robotised platforms appear on the commercial market for simple dedicated tasks: no doubt that the R&D focusing on the control will allow to extend those tasks to missions preserving the Human Life, such as Humanitarian demining, Rescue, Environmental Surveillance, etc.

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