State of the Art Review on Mobile Robots and Manipulators for Humanitarian Demining

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Abstract- **Robotics solutions properly sized with suitable modularized structure and well adapted to local conditions of dangerous unstructured areas can greatly improve the safety of personnel as well as the work efficiency, productivity and flexibility. In this sense, mobile systems equipped with manipulators for detecting and locating antipersonnel landmines are considered of most importance towards autonomous/semi-autonomous mine location in a proficient, reliable, safer and effective way. This paper reviews the most relevant literature and previous research activity regarding mobile robots and manipulators for humanitarian demining.**

I. INTRODUCTION

Detection and removal of antipersonnel landmines in infested fields is an important worldwide problem [1]. Landmines, cluster munitions, explosive remnants of war (ERW) and improvised explosive devices (IED) are an enduring legacy of conflict. These devices can remain active for decades, they are not aware of negotiation or peace treaties and do not distinguish between soldiers and civilians. AP mines and unexploded devices (UXO) of the Second World War still exist in all the countries of Europe and North-Africa [2]. In 2010, a total of 4191 new landmine casualties were reported, 5% more than in 2009, and a total of 72 states, as well as seven disputed areas, were confirmed or suspected to be mine-affected [3]. The problem of hidden IEDs has become especially worried. These homemade bombs came to prominence during the wars in Iraq and Afghanistan, but now these ghastly devices are proliferating around the world. The number of such bombing has increased from close to zero a decade ago to more than 4000 per year in Afghanistan alone [4]. A high mine-clearance rate can only be accomplished by using new technologies such as improved sensors, efficient manipulators and mobile robots. Mobile systems equipped with manipulators for detecting and locating antipersonnel landmines are considered of major relevance towards autonomous/semi-autonomous mine location in an efficient, reliable, safer and effective way. Robot mobility, manipulator dexterity and energy efficiency are some of the key points for future development. This paper reviews the most relevant literature and previous research activity [5-8] regarding mobile robots and manipulators for humanitarian demining being its main purpose to help outlining the main features, requirements and specifications, for the next generation of mobile robots to be developed in the frame of the TIRAMISU EC project (Grant Agreement n° 284747). The paper summarizes the information of the previous IARP workshops, complemented by some recent progresses achieved at the RMA, CSIC and ISR-UC.

II. THE PROBLEM

In 1994, the United Nations Mine Action Service (UNMAS) was founded, with as objectives the mine awareness and risk reduction education, the minefield survey, mapping, marking and clearance, the assistance to victims, the advocacy to support a total ban on AP-mines, and, in 1999, the treaty of Ottawa (the Convention on the Prohibition of the use, stockpiling, production and transfer of AP-mines and their destruction) entered into force.

The military de-mining operations accept low rates of Clearance Efficiency (CE). For these purposes it is often sufficient to punch a path through a mine field. But, for the humanitarian de-mining purposes, on the contrary, a high CE is required (a CE of 99.6% is required by UN). This can only be achieved through a 'keen carding of the terrain, an accurate scanning of the infested areas': that implies the use of sensitive sensors and their slow systematic displacement, according to well-defined procedures or drill rules, on the minefields. At present, hand-held detectors seem still to be the only and most efficient tools for identifying all unexploded ammunitions and mines, but this first step doesn't solve the problem: the removal task and/or the neutralisation and/or destruction task must follow, and those last two tasks are also very time-consuming actions. So the importance of fostering robotic technology advancements into the humanitarian demining context is considered of major interest in two main directions: improving operational performance and decreasing operational risks by means of demining task robotization and by separating as much as possible human operators from the direct exposure to threat.

III. MOBILE ROBOTS AND MANIPULATORS

A. Mobile robots

Conventional vehicle-mounted mine detector systems employ an array of sensor devices to achieve a detection swath typically 2~4m wide. Some systems employ more than one type of sensor technology. These systems, while being very useful are often expensive, unsafe, complex and inflexible [9-11]. Nevertheless, several IARP workshops [12-13] have on the contrary shown that the use of Robotics Systems could improve the safety and the clearance efficiency and that they may be considered as promising tools. However, the development of a Robotics System (RS) implies the design, the reliability and the cost-effectiveness of its modular components: those ones that appear in Figure 1.

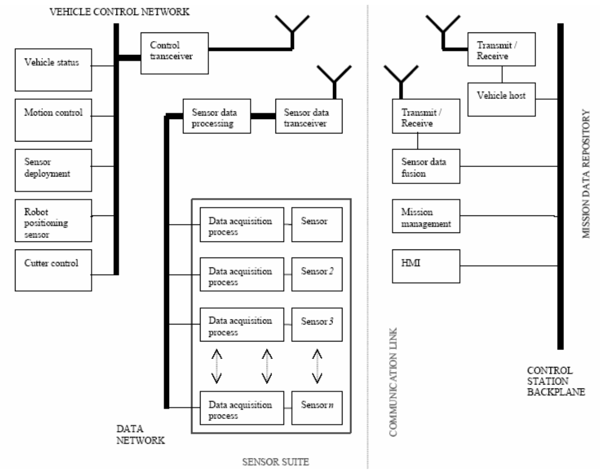


Fig. 1. Modular description of a Robotic System for the Detection of Explosive Devices

By other side, several mobile remote controlled platforms (with or without manipulators) have been described, some ones illustrated in Fig. 2.a to 2.h [for more information please refer to references: 1, 7, 10, 12, 13, 14, 15, 21, 27, 28, 29] where in most cases the motion control and the navigation sensory needs are highly sophisticated [16-24, 26].

General motion in difficult terrain needs advanced adaptive control, and closely controlled motion is required to deliver sensor packages to accurate positions when detection is in progress. The motion of the vehicle demands by far the highest power requirements. Whilst some scenarios allow the use of an umbilical, many need more autonomy so an on-board power supply is needed. Thus efficiency of motion is most important, requiring advanced control algorithms [25].

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 have a man-in-the-loop operation and there is a direct line of sight operation at a safe distance. This safe distance has to be specified and as is 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 machine to the remote command station. To carry out complex tasks, the numbers of cameras needed and their positions have to be considered. It is likely that at least two fixed or one rotational camera need to be fitted to the vehicle to give all round viewing during operation and allow the modelling of the ground. Recent developments with omnidirectional stereo tracking system have been reported [24].

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 is also required.

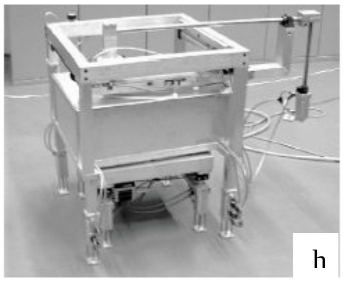
In summary, machines to carry out de-mining activities in place of human de-miners are generally likely to be wheeled or tracked. However, there is a possibility that in certain terrain, walkers will add value [1, 5, 6-7, 14, 21, 28]. Such machines are likely to be light in weight. The control and communications 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 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.

B. Manipulators for scanning/sensor handling

Manipulators are employed in many mobile robots [5, 6, 7, 9, 10, 12, 14, 21-23, 29] with the mission of handling sensors and to perform the sweeping/scanning of the interested surface. This is indeed a complex task. For example when using GPR (normally used in combination with a Metal detector), the signal is strongly affected by a ground surface. If it is not flat and even, a reaction from ground surface varies much stronger than that from landmines. In addition, this variation of reaction from a ground surface disturbs an imaging of landmine, occasionally cancels it out. It’s consequently mandatory to design an adaptive scanning of the ground surface to reduce the effect of a bad positioning on the useful reflection signal.

Fig 2: a) Gryphon-IV. Tokyo Institute of Technology, JP; b) COMET-III – Chiba University, JP; c) Mine Hunter Vehicle, with teleoperated hydraulic manipulator, Chiba University, JP; d) SILO6-DYLEMA, six-legged autonomous demining robot with 5 dof electrical manipulator, CSIC, ES; e) LADERO, pneumatic demining multi-sensor legged robot, ISR-UC, PT; f) Mine detection robot Hunter-ROBUDEM, Royal Military Academy, BE; g) 16-wheeled Sensing Vehicle, Tohoku University, JP; h) AMRU-4, eight-legged electro-pneumatic sliding robot, RMA, BE



Proximity sensors attached directly to the sensor head can be a very simple solution for a reflexive control scheme to automatically adjust the vertical distance of the sensor head to the terrain [10, 12, 13, 21, 26, 29]. However, although technically more complex and expensive, in order to make possible a more efficient mapping and scanning of wider areas in a minimal time, cameras and/or laser range finders have to be used.

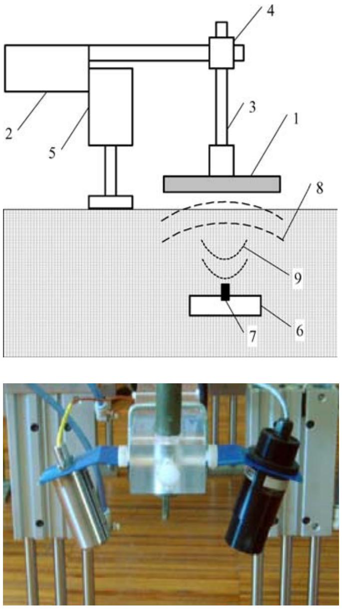


Fig. 3. Position of the metal detector on the robot. 1: metal detector, 2: robot platform, 3: support, 4: height adjusting unit, 5:pedipulator, 6: mine, 7: metal part of the mine, 8: transmit field, 9: receive field (top) and infrared sensor (down). ISR [30].

Figure 3 illustrates the use of IR sensor that together with computer vision was succesfully employed for terrain mapping [30].

The passive stereo system has been selected for the GRYPHON-IV (Fig 4.a,b), working in two steps: first the generation of a regular grid that will be overlapped to the terrain image, then the computation of the commands to the actuators of the 5-DOF manipulator carrying the multi-sensor-head. Mono system results obtained with RMA-Hunter are presented in Fig. 4c [11]. By other side the 5-dof manipulator on-board SILO-6 has been used for terrain mapping using a number of IR sensors placed around the MD (Fig. 4d) [26].

C. Robot positioning and tracking.

The ability to track the pose of a mobile robot, relative to its environment, while simultaneously building a map of the environment itself, is a critical factor for successful navigation in a partially or totally unknown environment. Simultaneous localization and map building (SLAM) has therefore been a highly active research topic during the last decade. While most existing approaches to SLAM make use of sonar or laser scanners, the use of vision sensors, both stereo and monocular, has also been studied, mainly because vision can yield a much richer information about the environment when compared to other kinds of range sensing devices. Omnidirectional stereo tracking system presents the advantage of full 360º view with mechanical simplicity of implementation [24].

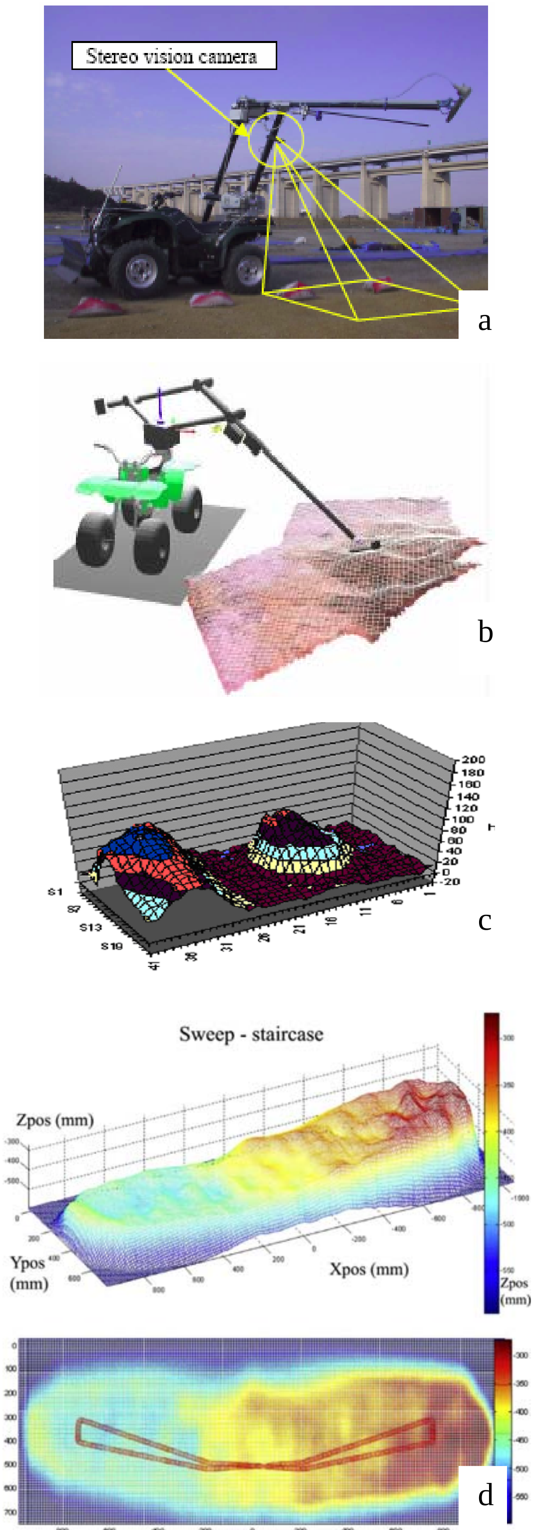


Fig. 4. .Stereo system results on GRIPHON-IV (a,b) [12], Mono system results on RMA-Hunter (c) [11], and validation of ground-surface-contour map generation with CSIC-SILO-6 (d) [26]

Finally, let us also mention that a good positioning accuracy can be obtained with commercial systems such as DGPS (Differential Global Positioning Systems) for so far the communications allow their use [27].

D. Robot control system

As previously mentioned, and as clearly pointed in the Fig.1, a Robotics System is not limited to a mobile platform, but includes proprioceptive and exteroceptive sensors allowing the precise actuation of the mechanical parts of the robot as well as the precise positioning of the robot self, and, in the case of Humanitarian de-mining, the detectors of the explosive devices. Furthermore, even if this solution may not be expected at short term, several robots may be used on the same minefield with dedicated de-mining tasks (brush-cutting, detection, removal, etc.). 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 targeting Tele-operation. For example, the RMA chose this last base to develop COROBA, 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.

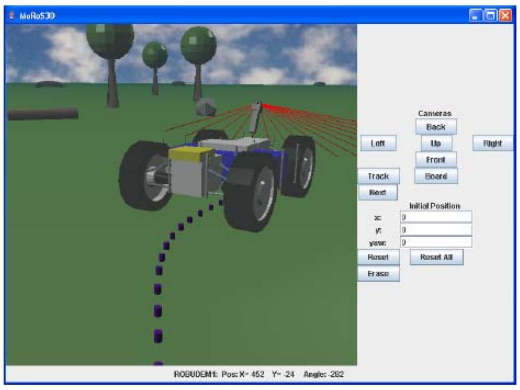


Fig.5. Virtual world

Figure 5 presents virtual world 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. At this stage, real implementations are realized on a outdoor robot ROBUDEM and an indoor one NOMAD.

IV. CONCLUSIONS

The development of a Robotics System not only depends on the technical aspects and modular components allowing the correct design of the remote controlled platform(s): the application related constraints have also to be carefully analysed in order to achieve the success of the whole system. Technically, the next scheme (proposed by the European Consortium CLAWAR) perfectly describes the hard- and software modules we have to focus on. The constraints related to the Humanitarian De-mining, and more generally to outdoor applications, may be summarised as follows: a high level of protection against the environmental conditions (dust, humidity, temperature, etc.), protection and resistance against vibration and mechanical shocks, long and continuous operation time between battery charging/changing or refuelling, wireless communication range depending on the terrain and minefield location, low cost, affordable prices by use of off-the-shelf components (typical constraint for HUDEM due to the lack of a real commercial market), high reliability, fail-safeness, easy maintenance, easy to use, application of matured technology. An ISO SC2 Technical Committee started the study of standards for mobile ROBOTICS (Catania, 23 Oct 2005 – final Clawar meeting). The paper is completed with next annexes, based on informations collected during the IARP workshops and allowed by their POCs, summarise the actual status of Robotics Systems. Test and Evaluation criteria are proposed as well, as result of WS discussions.

V. ACKNOWLEDGEMENTS

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ANNEXES

Important Note:

1. **The presented photos, robot data and drawings are drafts actually submitted by their authors. No reproduction is allowed without the written consent of them or of the IARP/WG Hudem Chairman (Yvan.baudoin@rma.ac.be)**
2. **New data may be added on request and are welcome (contact IARP/WG HUDEM) too**
3. **This data collection is adapted after each IARP WS HUDEM. The next one reflects the state of the art by end March 2012**

TITLE	COUNTRY
Introduction SOTA	**IARP - RMA**
HUNTER-ROBUDEM	**BELGIUM**
LADERO	**PORTUGAL**
DYLEMA/SILO-6	**SPAIN**
TRIDEM	**BELGIUM**
COMET II - III	**JAPAN**
AMS	**JAPAN**
GRYPHON IV	**JAPAN**
M HUNTER V	**JAPAN**
Other Robots, T&E criteria	**IARP WS Source**

TEST and EVALUATION

The next text will be adapted by mid 2011 to take into account with the current standards.
Two schemes have to be taken into account: the scheme of the figure 1 (Robotics System) and the modular specification defined in CLAWAR. Two major levels have to be considered when testing and evaluating a Robotics System, namely the system self, then the robot.
A robot may not be used in all possible circumstances and environmental conditions. It also has to be considered as a mechanical intelligent assistance that will be exploited if necessary. It's the reason why tests may not exceed the expectations of such a tool and why every robot belonging to this catalogue includes its actual capacities.
As an example, a large Tele-operated robot used in an agricultural zone will not have performances comparable with a multi-legged robot intended for assistance of some de-mining teams in a woody area.
Both systems will be quite different in size, locomotion, power, speed, etc.
First, in general, the robotics system should be tested at system level (figure 1) unless it can be shown that system integrity does not contribute to the specific results. The criteria Si (table 1 below) have to be verified if they correspond to the environmental conditions wherefore the system is proposed. Only some requirements have to be satisfied whatever the envisaged use of the RS.

SYSTEM LEVEL REQUIREMENT

The basic performance, at the Robotics System level, lies obviously in the correct (precise) mapping/detection of (a) pre-defined dummy minefield (s). All the modules (figure 1) aiming the working of the robotics system has to be evaluated during the trials. The minimal performance is fixed by this one obtained by a manual team in same circumstances. The next table only focuses on the use of a mobile Ground Robot carrying detection sensors.

S1	Map points (identified locations of mines from the mapping procedure) shall be accurate to within 50x50 cm² area, at least
S2	Control, communications and mine detection electronics should be insensitive to occasional explosions, shocks during the transportation and operator errors
S3	The system shall operate within the geographical (local) temperature range
S4	The system shall operate within the local humidity range
S5	The system shall be capable of detecting all mine types in *all- local* environments
S6	All components of the system shall communicate with a central controller, with progress information
S7	Communications equipment shall not interfere with the detection process
S8	Communications equipment shall not cause the detonation of any mines
S9	All sensor and electronic sub-systems shall be integrated without interference
S10	General safety/security related ISO have to be applied.

*Table 1. **SYSTEM LEVEL REQUIREMENT***

R1	Each robot shall be small enough to be portable (by manned ground transportation to access the minefield or to be removed from the minefield in case of failure), easy to transport and deploy
R2	Each robot shall have a mean-time between failures of , at least, 1 month
R3	Each robot shall be fail-safe on the minefield; it should have suitable mechanism for self-

	recovery for some levels of the problems that may face during it works
R4	Each robot shall have navigation capabilities allowing him to navigate to a map-point of a mine. It must have a localisation capability of its sensors.
R5	There shall be scanning equipment on the robot(s) to scan for dangerous terrain in front and behind the vehicle when it is been located at a specific map-point
R6	The robot shall be 100% reliable in clearing (detecting) mines
R7	The robot shall move effectively over longitudinal slopes of up to 25 %
R8	The robot shall move effectively over lateral slopes of up to 15%
R9	Sensor deployment will be such that Mine detection sensors shall identify mines down to depths specified at varying orientations in varying soil and vegetation conditions
R10	A de-mining robot should be self-contained (i.e.no ombilicus)
R11	All robots shall carry a marking system on board
R12	All robots shall be capable of operating for at least four hours of land-mine clearance before being refueled (recharged)
R13	The robot navigation systems shall be provably correct and convergent
R14	The robot control system shall be provably stable
R15	The robot shall traverse a variety of terrains: slippery surfaces, soft soil, hard core
R16	Operator safety should be guaranteed
R17	It should be capable of withstanding explosive blast without suffering major damage. At the minimum, the High Tech parts of the robot that can not be replaced locally should be well protected
R18	The man-machine interfaces including the ergonomic of lightweight portable control stations, friendly users
R19	The platform should not, through its design, limit the potential of the sensors. The operational conditions should be limited only by the detectors'capabilities
R20	The mechanical and electrical design should be modular, and the control architecture should include a high level application programming interface permitting upgrades and placements to sensor payloads throughout operational lifetime

Table 2. ***ROBOT LEVEL REQUIREMENTS***

With those minimal requirements in mind, Procedures suggested by the STANAG 4587 and the NATO RTO SCI-133 working group on "Countermine Technologies" may be adopted as well, and in particular:

(i) For the robot considered as a mobile platform:

- Mobility Testing
  - Transportability
  - Mobility to operations site
  - Mobility on off-road slopes (climb, descend, cross-slope)
  - area scanned in given period of time.
- System Robustness
  - Number of equipment breakdowns
  - Man-hours and parts to repair
  - Equipment modification recommendations
  - Blast effects on platform structure and mobility
- Logistic Support (POL and spare parts)
  - Daily POL/ELEC logs (oil, batteries, etc)
  - Operating hour consumption rates
- Maintenance
  - Scheduled, including daily, maintenance actions, time and parts
  - Unscheduled maintenance actions, time and parts
  - Percent of test time devoted to scheduled and unscheduled maintenance
  - Available manufacturer, dealership support
- Required Facilities
  - Storage facilities
  - Maintenance facilities
- Support Staffing and Associated Training
  - Unique mechanical maintenance
  - Unique electronic equipment maintenance
  - COTS equipment support

(ii) For the robot considered as a remote controlled platform

- Human Factors and Operator Comments
  - Visual, audio issues, communications (HMI)
  - Navigation issues
  - Tracking/positioning precision
  - Ease of updating the software control system
  - Ease of maintaining the hardware control system
- Blast/fragmentation Survivability Tests / module Fig 5 excluding detection sensors and mechanical structure)
  - Direct blast and bounding mine blast tests
  - Equipment survivability
  - Field reparability of blast damage
  - Time and parts to repair

(iii) For the robot considered as a mechanical sensor-carryer

- Blast/fragmentation Survivability Tests / module Fig 5 detection sensors)
  - Direct blast and bounding mine blast tests
  - Equipment survivability
  - Field reparability of blast damage
  - Time and parts to repair
- Sensor data transmission/processing
  - Reliability of transmitted data
  - Interpretation
  - Area cleared / hour (including the reaction/action times by each detection)