Robust perception algorithm for road and track autonomous following

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ABSTRACT

The French Military Robotic Study Program (introduced in Aerosense 2003), sponsored by the French Defense Procurement Agency and managed by Thales Airborne Systems as the prime contractor, focuses on about 15 robotic themes, which can provide an immediate "operational add-on value".

The paper details the "road and track following" theme (named AUT2), which main purpose was to develop a vision based sub-system to automatically detect roadsides of an extended range of roads and tracks suitable to military missions. To achieve the goal, efforts focused on three main areas:

- Improvement of images quality at algorithms inputs, thanks to the selection of adapted video cameras, and the development of a THALES patented algorithm: it removes in real time most of the disturbing shadows in images taken in natural environments, enhances contrast and lowers reflection effect due to films of water.
- Selection and improvement of two complementary algorithms (one is segment oriented, the other region based)
- Development of a fusion process between both algorithms, which feeds in real time a road model with the best available data.

Each previous step has been developed so that the global perception process is reliable and safe: as an example, the process continuously evaluates itself and outputs confidence criteria qualifying roadside detection. The paper presents the processes in details, and the results got from passed military acceptance tests, which trigger the next step: autonomous track following (named AUT3).

Keywords: Autonomy, Road detection, Road following, Track, Fusion, Shadow, Robust vision

1. INTRODUCTION

In the very beginning of year 2000, the French Procurement Agency (DGA) launched a Robotic Advanced Studies Program (RASP) to improve functionalities and performances of tele-operated UGV for land battlefield missions. This four-year program focuses on battlefield robotic technological gaps in order to increase the operational interest in robotic systems. It involves several of the major French robotic companies and labs, with Thales Airborne Systems selected as prime contractor [1].

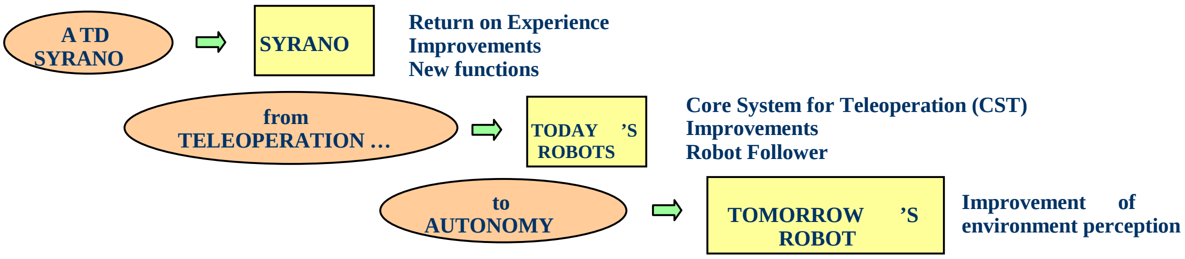

Fig. 1. Robotics Advanced Studies Program three axes of effort

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Split into about 15 technical studies grouped into 3 major themes, the RASP concentrates on issues, which can provide an immediate operational add-on value. Thus, most of the studies results have to be **demonstrated on existing experimental robotic systems.**

The goal of **the first theme "SYRANO improvement"** is to develop and add robotic functions progressively to SYRANO ATD, as their performances can improve the system overall operational credibility [2]. **The second theme "Teleoperation"** includes studies to improve capabilities of generic teleoperation for land battlefield purposes, using state of the art robotics, and based on a Core System for Teleoperation (CST) allowing to quickly transform a large variety of standard vehicles into teleoperated ones with functions from low level teleoperation to autonomous modes ("Leader Follower", obstacle avoidance, etc.).

Fig. 2. SYRANO Operational Demonstrator

Fig. 3. Core System for Teleoperation (CST)

The aim of **the third theme "Autonomy**" is to prepare the next generation of military robotics, not as fundamentally new systems, but as smooth evolution of tele-operated robots. We are convinced that tele-operated functions and autonomous capabilities will be both part of future robotic systems, and will be used alternatively or concurrently according to operational context requirements.

It appeared that to improve autonomy for mobile robots means **to improve perception capabilities**. Indeed, many onboard autonomous functions are already developed and used giving the ability to fully automatically perform the start sequence taking into account all potential disturbances (slope, stalling, etc.), replay a pre-recorded trajectory, face holes of communication with *Retrotraverse* mode and strategies based on the automatic switch to different links of communication, etc. To go further in terms of autonomy in order to relieve even more the tele-operator of mobility control tasks and increase robustness and reliability, the robots need to better feel and understand the environment in which they evolve. In other words, perception needs to be improved.

Since "Perception for mobile robots" is a vast domain, the range of the study was first constrained to Vision considering three main motivations: this technology is already present on all tele-operated robots; Digital and analog cameras are sustained by civilian market leading to better performances at a lower cost; And finally these are passive sensors which is of great interest for some operational applications.

Among the many vision-based functions that might be found in the literature [3], the choice has been made according to the RASP program objectives, which are to identify, to improve, to carry out and validate **relevant and enough mature technology and algorithms**. This implies that, first of all, they should fulfill an identified military need and moreover that a demonstrative level could be reached by the end of the RASP. Therefore, after an analysis and comparison of state-of-the-art algorithms [4], named AUT1, the **road and track recognition and following** theme was chosen.

2. OBJECTIVES AND ISSUES

As clearly presented in [3] and [5], road following has been mainly, but non-exclusively, addressed by United States (Autonomous Land Vehicle, ALV, Navlab of CMU), Japan, Germany (VaMoRS and VaMP at UBM, Prometheus, Primus, Daimler-Chrysler), Italy (ARGO) and France (Prometheus, LASMEA). Most of these systems are designed for well-marked roads, if not for highways, which is very restrictive in a military context. Those presented as designed for unmarked road detection always include implicit hypotheses on the contrast between the road and its boundaries, on geometrical characteristics of the road, etc. which make them operational only on specific tests grounds. Hence, we focused our efforts on developing a vision-based sub-system to automatically detect roadsides taking into account the following military constraints:

- **An extended range of roads and tracks suitable to military missions**: from unmarked roads to unstructured route and tracks
- **A minimal operating domain mastered and known:** a restrained operating domain, on which the system performs reliably well is preferred to a wider operating domain with punctually non-mastered false detections.
- **Auto-evaluation capability:** whereas the characteristics of highways can be very precisely described because they follow some construction rules, unstructured roads correspond to a very wide range of roads. The system developed in the RASP framework will never be able to deal with all of them. So, the process has to evaluate itself continuously and to output confidence criteria qualifying roadside detection. If this criteria is too low, the autonomous road following is stopped and the tele-operator can take the situation back in hand.
- **A high level of robustness required**: all disturbances excluded from most of the road detection system operating domain are to be faced: various road typology, slope, banking, hidden area, shadows, various road condition (dry or wet), different surfaces, etc.
- **Real time constraint**: cycle time and delays need to be compatible with autonomous route following at 30km per hour (~20 mph).

3. MEETING THE GOAL IN TWO STEPS

The development of this road and track following system has been split into two phases:

- **AUT2,** focused on **detection,** includes *System analysis and specification*, *System design*, *Algorithmic improvements*, *Realization*, *Evaluation of the embedded system of detection.*

- **AUT3,** focused on **mobility control and integration,** includes *Integration in DARDS ATD architecture*, *Control of robot's mobility after road detection*. This phase leads to the *realization of an* ***autonomous system of road and track following,*** and *performance assessment*.

AUT2, realized in co-operation with three French labs, CMM[1], LASMEA[2] and LIVIC[3], terminated at the end of 2003 and is then presented in details as well as the results got from passed military acceptance tests, which triggered the next step, AUT3.
There are two key points:

- **No single algorithm** can deal with all type of unstructured roads.
- Road and track detection consists in a **sensors acquisition chain** followed by a **processing chain**. The final result will depend on the weakest part of these chains, since the useful information that it may loose is no longer available for the following parts of the chain. Thus, it is not worth spending all efforts only on one part of it, if the other parts of the chain are not of the same quality level. Briefly speaking, it is just as important to improve the acquisition chain to provide images of good quality as to try to make algorithms robust to images imperfections.

So, to achieve the goal, efforts focused on three main areas:

- **Improvement of images quality** at algorithms inputs, thanks to the selection of adapted video cameras, and the development of a THALES patented algorithm: it removes in real time most of disturbing shadows from images taken in natural environments, enhances contrast and lowers reflection effect in water puddles.
- **Selection and improvement of two complementary algorithms** (one is segment oriented, the other region based)
- **Development of a fusion process** between both algorithms, which feeds in real time a road model with the best available data.

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[1] CMM: Centre de Morphologie Mathématique (des Mines de Paris), Fontainebleau, France.
[2] LASMEA: Laboratoire des Sciences et Matériaux pour l'Electronique, et d'Automatique, Clermont-Ferrand, France.
[3] LIVIC: Laboratoire sur les Interactions Vehicule – Infrastructure – Conducteur, Versailles, France.

4. GENERAL ARCHITECTURE

The system is composed of **a data acquisition unit, a processing unit and a Man Machine Interface (MMI).**

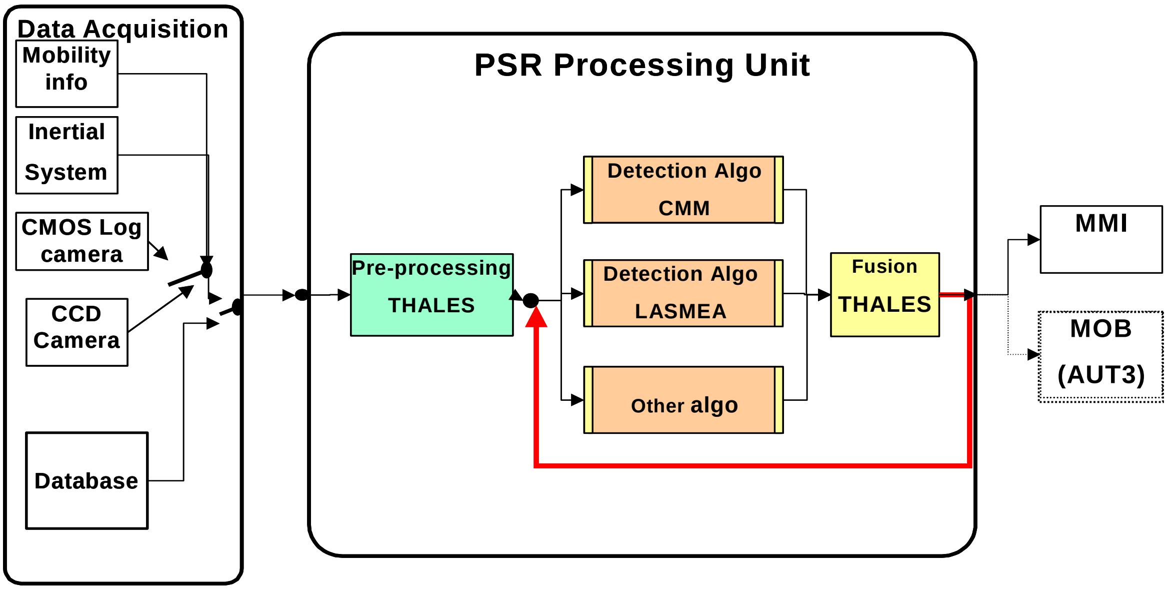


Fig. 4. General Architecture

The data acquisition unit includes:

- **A video camera:** a color CCD sensor or a CMOS Log one
- **An IEEE1394 frame grabber**, and its software interface with the acquisition system (RTMaps^{TM})
- **A camera calibration system**
- **Localization sensors: either a low cost configuration** with an odometer, an optic fiber gyros, and a two axis clinometer**, or a high performance configuration with an Inertial Navigation Unit,**
- **An acquisition calculator SYNAPSE**, also used as the processing calculator
- Specific **information from the Mobility control unit** of the robot (objective speed, level of allowed risk, etc.)

Instead of the sensor acquisition, prerecorded databases with synchronized multisensor acquisitions can also be replayed. To be optimized, this acquisition chain has been the focus of design efforts and of technological studies, which are described in part 5.

The processing unit includes:

- **A preprocessing**, developed by THALES, **to remove shadows and enhance the contrast** between the road and the borders
- **Two complementary unstructured roads detection algorithms**, working in parallel, delivered by the LASMEA and CMM labs.
- **A fusion process,** developed by THALES, taking advantage of the information from each detection algorithm in order to deliver a more accurate, reliable and rich estimate of the detected road.

The versatility of this architecture allows adding as many detection algorithms as wished, with few changes of the fusion. It is especially of interest to complete this system with marked road detection algorithms.
Preprocessing is described in part 6, detection algorithms adaptation, improvement and optimization in part 7 and fusion process in part 8.

Finally, <u>the MMI </u> has been realized with the RTMaps™ tool. In the AUT2 study, the outputs, i.e. **road boundaries, accuracy and reliability criteria**, are only **displayed**. In AUT3, they will be **sent to the Mobility control unit** for autonomous road following.

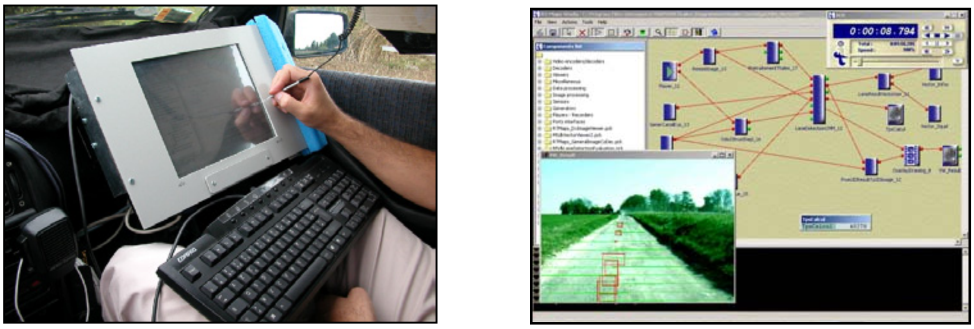


Fig. 5 AUT2 Man Machine Interface

5. ACQUISITION IMPROVEMENT

1. Approach

During the first phase of the AUT2 study, **five potential road detection algorithms** were **analyzed** in minute detail, in terms of approach, implicit assumptions, inputs, low level detector, road model, filtering, disturbance dealt with or neglected, performances (evaluate or expected) on each type of roads and tracks with several environmental conditions (rain, shadows, quick changes of light intensity, etc.). This fruitful analysis led to the choice of the two selected algorithms described in 7, but also underlined the sensitivity of the detection algorithms to the sensor acquisition chain. Some of the identified issues were:

- Choice of the sensor: numerous various situations ⇒ a wide range of luminosity, contrasts, etc.
- Most of the road detection algorithms work on B/W images, is it worth using a color camera?
- Field of view: in curves of small radius, the most part of the road cannot be seen in the image
- Some images formats involve compression. Which format suits best to the algorithms?
- Most algorithms are highly sensitive to shadows and low contrast in the images.
- …

Among this long list of concerns, some were put out of the scope of AUT2. For example, since the field of view issue is uncorrelated to intrinsic detection performance, and since it can be coped with by choosing a wide-angle lens and a few software adaptations (this will be done on the final robot platform of AUT3), it was not selected as a point of interest and small curves were temporarily taken out from mandatory operating domain. However, to improve performances and robustness, great efforts were spent on the other issues to **find out the best compromise between Performances, Evolution capability and Cost.**

First of all, for each component of the acquisition chain, **requirements** were expressed: color camera, video rate, high dynamic, medium resolution, processing power, OS, rapid hard disks access, etc.

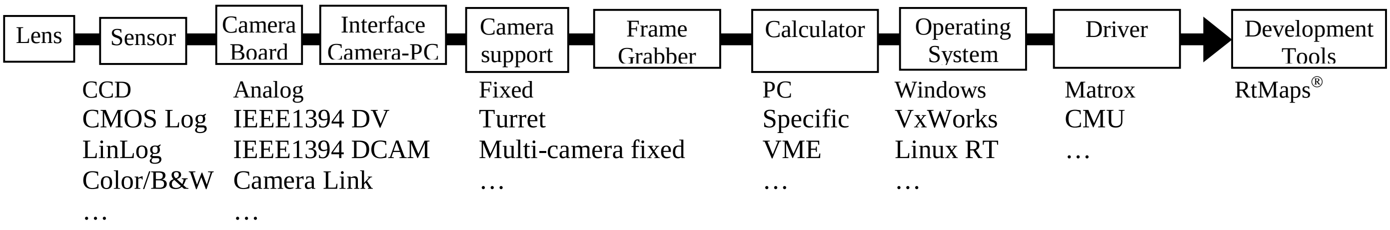


Fig. 6. Extract from the technological panorama for the acquisition chain

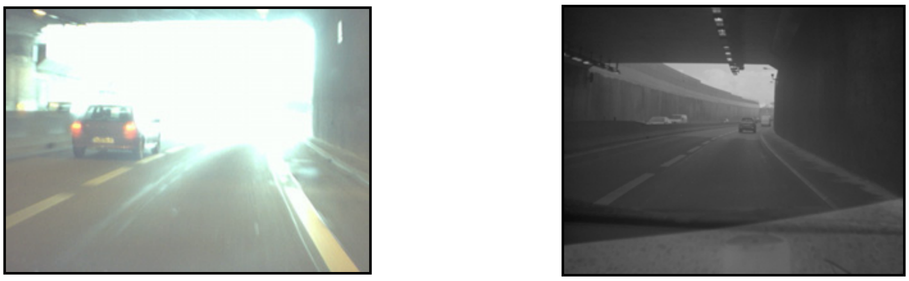
Then, these requirements were compared to an extended **technological panorama**. Figure 6 presents an extract of it. This gave us the keys to choose most components except the cameras!

2. Experimental camera benchmark program

Indeed, according to their datasheets, many cameras were fulfilling our requirements: uncompressed IEEE1394 DCAM color camera, 640x480, and 30 images per second. That is why a **vast experimental camera benchmark program** was launched in collaboration with the LIVIC lab. Many CCD and CMOS Logarithmic cameras, from Sony, Kappa, Basler, Vector International, etc. were tested, considering a great range of criteria:

- **in lab tests**:
    - Sensitivity to blooming and smearing
    - Color quality
    - Effective resolution
    - Sensor noise level
- **on road experimental tests:**
    - Blur and distortion due to movement
    - Dynamics in tunnels
    - Dynamics at night
    - Dynamics with low-angled sun

It is important to notice that the aim of this benchmark was to determine the best camera for our application. More precisely, for a given camera and a given scene, you will always manage to find a good parameters setting (sometimes after a 10 minute search) that leads to a nice image. However, in our embedded image processing application, the operator cannot change the parameters settings during the mission. In other words**, the key issue is the capability for automatic adaptation of the parameters settings in outdoor conditions**.



CCD CMOS Log

Fig. 7. Robustness of a CCD and a CMOS Log cameras in a highly contrasted scene

6. PREPROCESSING: SHADOW REMOVAL AND CONTRAST ENHANCEMENT

The first AUT2 phase underlined that all road detection algorithms are very sensitive to shadows and lack of contrasts. Shadows cannot be set out of the operating domain of an operational system since they can appear everywhere, owing to trees along the road, to the own robot shadow, etc. Nevertheless, there has been very few works on that subject. Previous works (e.g. [6] or [7]), based on narrow hypotheses, are efficient only for specific scenes, and, for example, cannot deal with shadows on brown road with brown borders, which is very restrictive. For these reasons, THALES developed its own Preprocessing algorithm. Its main features are:

- **Removes shadows**
- **Removes reflections** due to films of water
- **Extracts relevant information**: “contrast enhancement”

It is a **real time algorithm** with only 11ms for the 320x240 images used in AUT2. It has been **patented** in France [8], and other countries.

Figure 8 shows a typical result. While on the classical B&W image, shadows are the source of many false detection (whether they be region-based or edges-based techniques), the Preprocessing manages, thanks to an analysis of the color, to suppress the shadow contribution, and then to enhance the contrast. This is done without information about the position of the road in the image. It is effective whatever the color of the road and of the boundaries.

This Preprocessing makes **road detection easier**, but can also be used for other purposes. Indeed, this Preprocessing consists in extracting the most useful information from a color image and expressing it in a grey-level image. The resulting image can accept a very high compression rate.

B&W image Genuine color image Preprocessed image

Fig. 8. Shadow removal and contrast enhancement

B&W image Genuine color image Preprocessed image

Fig. 9. Small road in countryside. Illustrates the need for a high dynamic range camera: the small white areas on the road of the preprocessed image correspond to black-saturated areas in the genuine color image.

B&W image Genuine color image Preprocessed image

Fig. 10. Lowering of reflection effect in water puddles.

Fig. 11. Even if the road seems quite easy to detect here, it clearly shows the difference between a classical contrast enhancement algorithm and the Preprocessing. On the B&W image, the difference of the grey level between the left and the right borders is due to the sun lighting up the scene from the left. A classical contrast enhancement algorithm could only darken the left side and lighten the right one, while the Preprocessing gives the same grey level to both borders and offer a good contrast between these borders and the road.

B&W image Genuine color image Preprocessed image

Fig. 12. Shadow removal on a very unstructured road (with bad settings of camera parameters)

7. DETECTION ALGORITHMS IMPROVEMENT

1. Two complementary approaches

For the detection, two algorithms were chosen among most reliable today available algorithms: one from the LASMEA lab, the other from the CMM lab. Both developed during the last 10 years, they were initially designed for lane detection on motorways, cf. [9] and [10]. So, they needed a deep adaptation to unstructured road, but their strong initial base made it possible and worth it.

Above all, they are **based on very different techniques** at the lowest level as well as at the highest level. For example, the CMM algorithm is region-based, whereas the LAMSEA one is rather edge-based. The road model of LASMEA algorithm is a high degree one (a clothoid), whereas the CMM one is a low degree one with only two lines. Analyzing all these particularities, we expected a great benefit from this complementarity. In addition:

- to increase reliability of the road estimate by confirming or invalidating the other algorithm detection,
- and to improve accuracy of the road estimate,

it was expected, that in many cases, when one algorithm would fail, the other should succeed. In part 9, some examples illustrate that our expectations were satisfied.

Fig. 13. LASMEA's algo initial environment, CMM's algo initial environment, AUT2 Objective environment.

2. Adaptation to unstructured environment

Main improvements on the LASMEA algorithms concerns[4]:

- **Adaptation of the detection step:** a study on several hundreds of images was achieved in order to choose from several detectors (Canny, Mahalanobis, best transition, Deriche) the best suited to the task.
- **Improvement of the recognition criterion**: dependent on the quality of the low-level detection, on the part of the road visible in the image, on the algorithm phase (training step or tracking step), etc. In particular, this improvement allows now to detect and follow one border, e.g. for ditch or wood edge following.
- **Taking into account proprioceptive data:** odometric displacement, yaw and pitch angles.

Similarly, main improvements on the CMM algorithms concerns[4]:

- **Adaptation to Preprocessed images:** based on a Watershed Transformation, CMM adapted the low-level detection criteria and the hierarchical segmentation using several morphological filters.
- **Improvement of the road model estimation,** to be compatible with small curved changing-width sloping roads.
- **Optimizations:** Initial algorithm was too time greedy (800ms per image). So, the size of images had to be reduced (still keeping a good level of detection) and the code was optimized to reach a 40ms per image algorithm.
- **Design and development of reliability criteria**

Each algorithm was evaluated on SYNAPSE (a 2.0GHz bi-processor PC) to identify performance improvements brought by each modification.

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[4] Details on these works are to be published soon by LASMEA, CMM and Thales.

8. A THREE LEVEL FUSION

1. Methodology

Where? As shown on figure 4, fusion is not only one box, one module, of the diagram, developed by THALES, which takes advantage of many detection results. Fusion is, first, part of the architecture and interface design, like the feedback of the fusion result to the detection algorithms, giving them the opportunity to take benefit from it, for example when one does not manage to detect the road, while the other do.

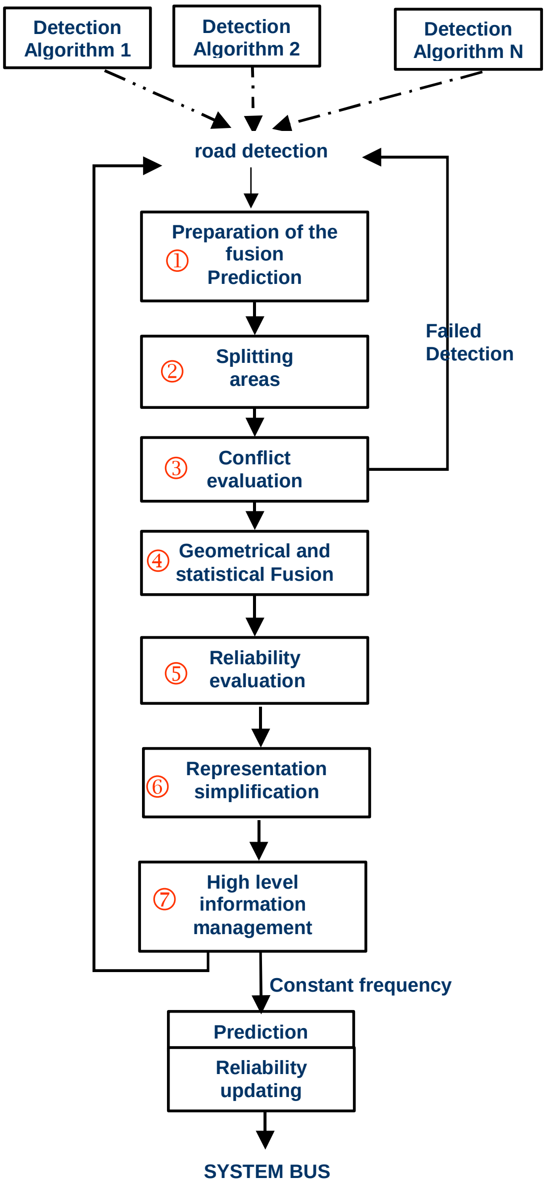


Fig. 14. The Fusion process

The second important point is **what** to merge:

- **Geometry** of the road estimate
- **Accuracy** associated to the estimate
- **Reliability** associated to the estimate

In this way, the result of the fusion process includes all information needed by the Mobility Control Unit to take the decision to follow the detected road according to the level of allowed risk.

How to do it? Our fusion process is:

- **deeply linked to operational requirements,** allowing some hypotheses but also imposing some requirements.
- **based on classical theoretical concepts**: Kalman, reliability, credibility, etc.
- **designed in a "natural way"**: it is not a black box that outputs an "unpredictable" result. Very few parameters are used, and they all have a clear physical meaning.

2. Principle

The fusion module feeds in real time a road model, updated after each road detection received from one detection algorithm. It is not limited by the number of detection algorithms, and can also process the detections containing only one border of the road.

Each time a detection algorithm outputs a detection, a first prediction step brings the detection and the fusion estimates to the same time reference. Road models are then split in smaller areas to ease phases 3 and 4.

The 3rd step, *Conflict evaluation*, consists in measuring the distance between both estimates, in terms of overlapping, to check if the detection result corresponds to the same road as the one tracked by the fusion process. If the distance is too high, either the road detection is rejected as a false detection (filtering), or the fusion process is re-initialized according to the road detection under some conditions of reliability of the detection.

The 4th step updates the fusion model according to the detected road model. It is a « Kalman » based process weighted by the normalized criteria of reliability of each algorithm. Then, the reliability of this new fusion estimate is evaluated. Based on local and synthetic reliability criteria, managed by a recurrent series taking into account lack of detection, it gives a reliability index to the Mobility unit and the operator, and helps to manage wrong detections and under-estimations due to the slope. The representation is then simplified, and high level information that might be provided by some algorithms (crossings detection, etc.) are integrated in the final result, which is periodically sent to the system bus.

This fusion has extended the operating domain and improved accuracy and reliability. Results are presented in part 9.

9. VALIDATION AND PERFORMANCE ASSESSMENT

A step by step evaluation was used to justify each improvement, giving a performance assessment of each detection algorithm and underlining the contribution of preprocessing, improved detection algorithms and fusion. Criteria were **Robustness, Accuracy, Reliability** and **Information extent.**

This evaluation was conducted from **prerecorded multi-sensors databases** and **embedded on the platform**. On one hand this gives the ability to compare on a same sequence the evolution of the performance due to algorithms improvement, and on the other hand, this allows to assess the performance on unknown video sequence and to demonstrate the capacity of road and track detection in real–time with an embedded system.

The final demonstration was in September 2003 and the Customer declared himself satisfied with the developed system.

Below are presented some representative results.

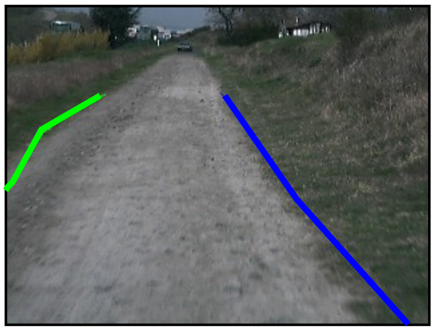
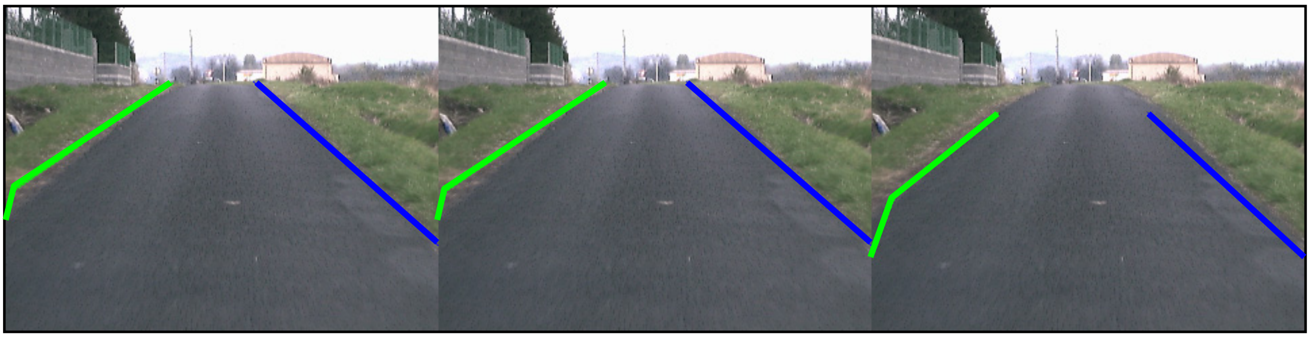


Fig. 14. Two-border detection

One-border only detection

DARDS, Technical Demonstrator



CMM FUSION LASMEA

Fig. 15. A rather easy situation To be noticed: the distance of visibility of the fusion estimate (i.e. furthest point detected as a part of the border of the road) is always at least as big as the biggest one of the detection algorithms.

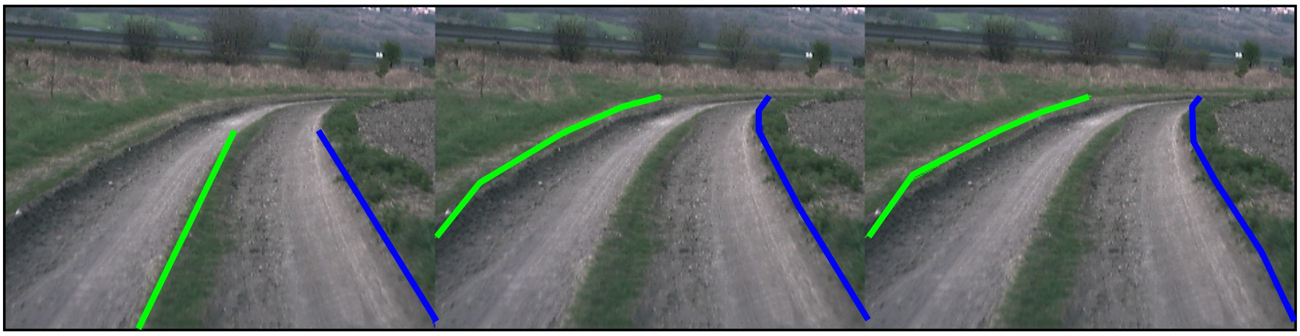


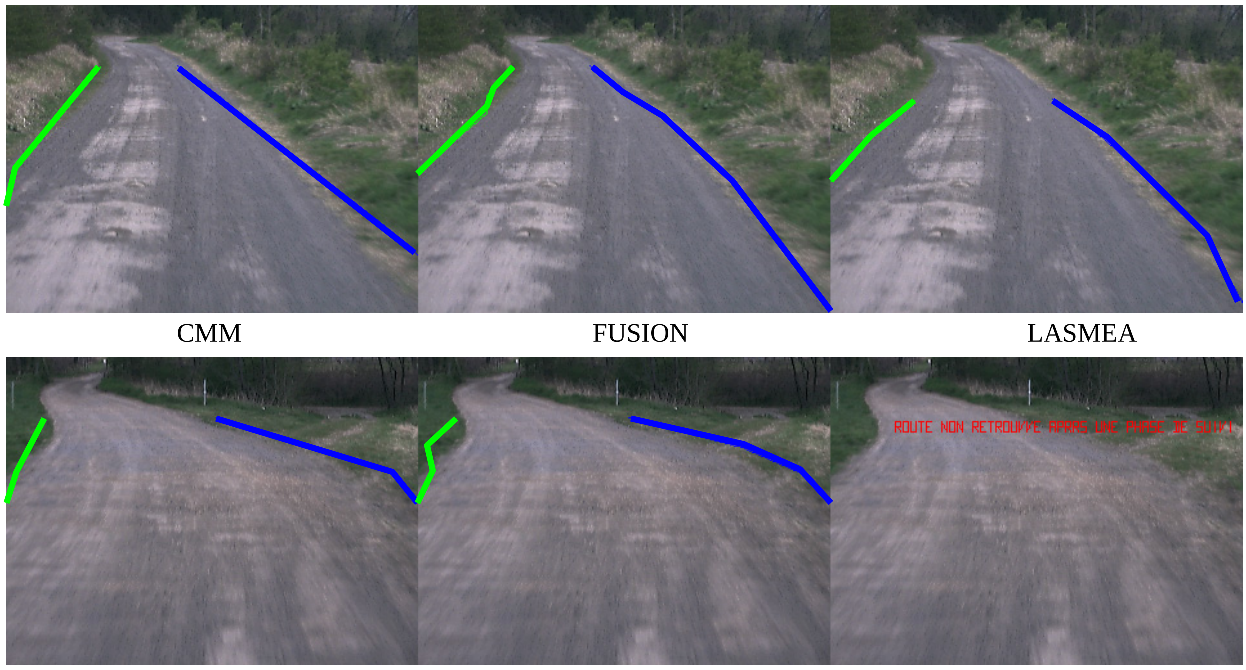
Fig. 16. Fusion filtering: Rejecting non-compatible road detection after geometrical criteria and conflict evaluation

CMM FUSION LASMEA

Fig. 17 Detection in a difficult situation: tracks with a central strip of grass. Quality of detection and fusion contribution.

CMM FUSION LASMEA

Fig. 18. Fusion is not a simple average of two results but takes into account accuracy of each part of the detection: on the upper part, Fusion result is almost not affected by LASMEA result since the accuracy associated to this part of the detection is very high (not displayed in the image). Algorithms are very robust to changes in road color.



CMM FUSION LASMEA

Fig. 19 & 20. The great contribution of fusion:
1st line: The fusion takes advantage of the better accuracy of LASMEA result. More precisely, LASMEA high degree model can better fit the border of the roads than 1st degree CMM model.
2nd line: Just a few seconds later, the fusion takes now advantage of the better robustness of CMM algorithm towards rapid change of road width or crossings comparing to LASMEA algorithm, which failed to detect the road.

10. CONCLUSION AND NEXT STEP

As presented, the road and track detection system developed has unprecedented performances in terms of operating domain extent, robustness and reliability. To go even further, some improvements have already been identified, especially to filter false detection, and their implementation is in progress.

The next step, AUT3, dedicated to the control of robot's mobility after road detection, started in 2004 and is leading to the realization of an autonomous road and track following system, and its performance assessment. Final results and demonstration are expected at the beginning of 2005.

In order to get a real operational function allowing to let the robot autonomously follow a road, the system should also be able to face potential disturbances, which, on a road, are obstacles and crossings. Some works on these topics have been initiated by THALES and have given very promising results. They will be completed and integrated in the system.

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