Airborne Collision Avoidance System as a Cyber-Physical System

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DOI: 10.13111/2066-8201.2015.7.4.12

Received: 12 July 2015 / Accepted: 24 September 2015

Abstract: *In this paper the key concepts of ITS - Intelligent Transport Systems, CPS - Cyber-Physical Systems and SM - Smart Mobility are defined and correlated with the need for ACAS – Airborne Collision Avoidance System, as the last resort safety net and indispensable ingredient in civil aviation. Smart Mobility is addressed from a Cyber Physical-Systems perspective, detailing some of the elements that this entails. Here we consider the Air Transportations System of the future as a Cyber-Physical System and analyze the implications of doing so from different perspectives. The objective is to introduce a 4D collision avoidance shield technology which forms a last resort safety net technology for the next generation air transport (2050 and beyond). The new system will represent a step change over the performance of current technology. As conclusions, the benefits of implementing Transport Cyber-Physical Systems are discussed, as well as what this would require for future deployment.*

Key Words: *CPS, Collision Avoidance System, Smart Mobility, T-CPS, Smart Vehicles, Smart Infrastructure, Multimodal Transport.*

1. INTRODUCTION

In our modern days the only practical possibility to meet the requirements for Smart Mobility is based on the necessity for our transportation system to evolve towards an Intelligent Transportation System (ITS) [1]. All individuals are, up to a certain degree, users of transportation systems as either passengers, consumers or operators. Due to the simple fact that generally it comes to a point where it is far too expensive to increase the capacity of, for example, a highway system by building more and more new roads, the consensus is generally admitting that adding intelligence to the system is a cost-effective long term solution.

Cyber-Physical Systems (CPS) concept has the potential to provide the technology and the implementation framework for a multimodal transport system meeting the requirements for accessibility, affordability, safety, resilience and to be orientated towards the user needs, as requested in a Smart Mobility society (fig. 1). The user of a such a system will be provided with a large variety of information about roadside services, alternate routes, safety scenarios

(including collision and crash avoidance) and comfort. An ITS is the only possible approach to solving the critical problem of reducing traffic congestions and increase safety (mainly with respect to vehicle crashes), and it is highly unlikely that any single solution outside an ITS will produce a quick fix, given the complexity of the problems associated with the movement of people and even material from one location to another [2].
The ITS is an integrator at system level for individual solutions with synergies. Congestion in traffic is by definition addressed by either extending the infrastructure of by limiting the access using specific criteria. Development of information-based solutions to transportation problems was introduced as a first innovative solution, with many attractive features [2,3,4]. This is relatively inexpensive compared to building new roads or bridges; has low social and environmental impact and in addition to the primary goal of improving the safety and efficiency of roadway use, this can produce a number of secondary benefits by carrying educational or public relations messages.

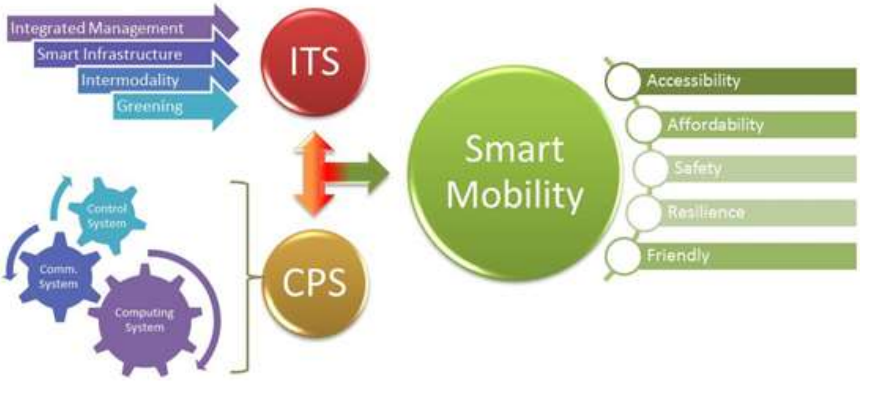

Fig. 1 – ITS and CPS contribution to Smart Mobility

Furthermore, CPS are increasingly developing in the transport sector. When considering the expected reduction in traffic congestion, reduced fuel cost and air pollution, improved navigational performance, decrease in the likelihood of accidents and improved driver efficiency, CPS are present in the Smart Car, Global Communication and the Intelligent Infrastructure concepts.
A critical milestone in the development of a CPS in aviation is the implementation of a new generation safety environment, able to meet current development challenges. Airborne Collision Avoidance System (ACAS) furnishes a last resort safety net and is therefore an indispensable ingredient in civil aviation. For example, the Traffic Alert and Collision Avoidance System (TCAS) implementation standard of ACAS is an integral part of the current air traffic management system and a key contributor to its high level of safety.
TCAS was however designed on technology that is already more than fifty years old and with air traffic operations of the previous century in mind. Despite numerous improvements in its functionality, this old technology basis of TCAS poses significant limitations on the further enhancement of ACAS. Most recent studies show that current TCAS II Version 7.0 provides on average about a factor 5 reduction in collision risk [5], and that the implementation of TCAS II Version 7.1 should lead to some 10% extra reduction [5,6]. A recent enhancement is the integration of TCAS II in the Autopilot/Flight Director for A380, with the option of human reversal by the crew [23]. Although this leads to a significant better response of the aircraft to TCAS, it does not solve the weaknesses that are inherent to the

half century old design and which creates major challenges in accommodating changes in future air transport. In view of this there is a need for a radical different approach to the last resort safety net in air transport.

2. STATE OF THE ART FOR AN AIRBORNE COLLISION AVOIDANCE SYSTEM

Smart Mobility (SM) as originally introduced [3], is based on the use of Information and Communication Technologies (ICTs) infrastructure to improve the functioning of mobility systems, enhancing their efficiency, improving their competitiveness. In a techno-centered approach, ICTs represents the keystone for building up the SM. It relates the infrastructure of smart cities to their operational functioning and planning through management, control and optimization. At the same time SM is based on innovations for infrastructures, vehicles and services, looking at citizens as end-consumers (fig. 2).

Fig. 2 – Smart Mobility in a Smart City

Key technologies for Smart Mobility concept adapted to the need for a TCAS include the following:

Smart Infrastructure and Sensors - The crucial technological ingredients of smart infrastructures include low-cost sensors and clever software for data fusion (analytics and visualization), as well as computing power. Sensor networks are at the heart of all sorts of smart infrastructure. Each sensor node will integrate specific sensing capabilities with communication, data processing and power supply.

Examples include: Wireless Detectors, Smart Pavements, Passenger Counters, RFID Tags, Probe data-collection technologies, Eco Sensors, Automatic Vehicle Location, Weather Sensors, Vehicle Re-identification, Pay-as-Go units, Smart Cameras & Video processing, etc.

Smart Vehicles – single mode and future multimodal vehicles with advanced on-bord technologies.

Examples include: on-board technologies as Navigation System, Inertia Navigational Unit, On-board V2X Communication Box, In-Vehicle Network, Smart Display, Smart Camera, Driver Awareness Monitoring, Eco Sensors, Electronic Billing Unit, Streaming unit, Safety Driving System, In-vehicle information systems, Driver Identification, etc.

Smart Communications - Various forms of wireless communications technologies integrated on-board for intelligent transportation systems.

Examples include: Radio modem communication on UHF and VHF frequencies are widely used for short and long range communication within ITS, Short-range communications, etc.

Transportation Cyber-Physical Systems (T-CPS) already play a role in common daily life and economy[4]. This role is expected to increase in the future as higher levels of transport autonomy, safety, and convenience are achieved. The complexity of transportation systems as a whole, as well as smaller components such as vehicles, is growing at an exponential rate. Everyday tasks or events, such as commuting by automobile, train, or airplane, depend on complex yet reliable and seamless interactions between the vehicles' computer systems and physical systems embedded into the smart infrastructure, while under control by human operators or end users (fig. 3). Today's transportation systems are being designed to be more competitive within their respective industries by adding more complex features and capabilities to increase energy efficiency and safety.

Fig. 3 – Transport Cyber Physical Systems (T-CPS)

The major impact for the development of CPS is at vehicle level. With the increasing deployment of sensing technologies at vehicle level, the focus was redirected towards intelligent infrastructures and, as a result, we are now facing new generation for transport systems that have been developed as a result of the T-CPS concept. This is mainly the case for Next Generation Air Transportation System (NextGen) – [4], which can be thought as a large-scale CPS. The cyber or computer components of automobiles, aircraft and other vehicles have been increasing and will continue to play a larger role in these systems. It is estimated that currently as much as 40% of an automobile's value consists in cyber-physical components (electronics, sensors and actuators, and embedded software).

Worldwide areas where CPS can be applied benefit from the integration of satellite navigation and control of aircraft, advanced digital communications, advanced infrastructure for greater information sharing, and enhanced connectivity between all air transportation system components. Reliable, seamless integration of the technological and physical elements of the systems are essential for the safe operation of air transportation. This translates to increased automation in all parts of the system, ranging from aircrafts to ground infrastructure, communication systems, and air traffic controller decision support tools. Today, humans play an active role in both automotive and aviation operations. Although modern aircraft have a larger amount of automation, pilots still play an essential role in control and Unmanned Vehicles have yet to make a significant presence in the airspace (for civilian transport purposes).

There are currently a number of Current Autonomous Vehicle projects whose prototypes were successful:

- ***Google Car***. Google has developed numerous autonomous Toyota Priuses that have already driven more than 190,000 miles in city traffic, busy highways, and winding country roads. The Google Car drives autonomously using a large laser mounted on top of the vehicle, four radars, global positioning system GPS, and many other sensors to measure and react to the surrounding environment while avoiding obstacles and obeying traffic laws.

- ***DARPA Urban Challenge*** [6]. In 2007, the Defense Advanced Research Projects Agency held the Third Urban Challenge, in which competing autonomous vehicles had to drive in an urban environment among other autonomous vehicles as well as those driven by people.

- ***Grand Cooperative Driving Challenge*** [7]. The first Grand Cooperative Driving Challenge was held in the Netherlands in May 2011. Autonomous vehicles competed and had to communicate with each other while navigating urban and highway environments to perform cooperative driving.

In aviation, at EU level, there is a major development under SESAR (www.sesar.eu) framework program, aiming to the integration of RPAS – Remote Piloted Airborne Systems in the un-segregated civil air space.

The key enabler for proposing the development of such a step change is that we have identified a novel mathematical theory about guaranteed collision avoidance for objects that evolve according to a specific type of differential equations. In the scientific literature this theory is known under the name Navigation Functions [24]. So far this novel theory has successfully been applied to collision avoidance in the field of robotics. The evolution of flying vehicles satisfies differential equations which fall within the specific type covered by the novel theory.

Therefore this novel theory allows for each aircraft to “carry” a virtual 4D-shield which interacts with the virtual 4D-shields of nearby other aircraft. As a result of this interaction, these 4D-shields jointly produce guaranteed collision avoidance flows for the aircraft involved. In contrast to current logic based ACAS, Navigation Functions support a coordinated determination of the collision avoidance flows without the need of any decision making logic, and also free the human from tactical manoeuvring. Furthermore, the theoretical basis of Navigation Functions is such that it can well take into account the performance capabilities of each aircraft (e.g. manoeuvrability, lower and upper velocity bounds, degradation modes, etc) at any given time. This allows pioneering-ACAS to take a radical departure from conventional TCAS approaches, while covering a much wider range in air vehicle types and performance characteristics.

3. A CPS CONCEPT FOR ATM

Cyber-Physical Systems (CPS) are physical engineered systems whose operations are monitored, coordinated, controlled and interpreted by computing, communication and control [8]. They depend, most of all, upon the synergy of computational and physical elements. CPS are complex systems that are characterized by the tight interactions between the physical dynamics, computational platforms, communication networks, and control software (fig. 4). Many CPS are safety-critical control systems such as automotive vehicles, aircraft and industrial processes.

Fig. 4 – CPS concept outline

CPS are integrated computers with physical world, where sensing, decision, actuation, computation, networking and physical processes are mixed. Examples of CPS applications include: smart electric grids, smart building, smart transportation, smart medical technologies, smart manufacturing, next-generation air trafic management. The goal of implementing CPS is the deep integration of physical and virtual design, and thus CPS has taken us from „Computer for Control" (C2 Paradigm) to „Computer, Communication and Cognition for Control (C4 Paradigm)".

CPS require a large number of embedded devices, which are interconnected and connected to the Internet. As PC's processing power has become fast and communications using large bandwidth speeds is cheap, processing and communication capabilities will soon be imbedded in almost every surrounding physical object or structure. Thus CPS can be applied anywhere from large industrial scale to nano-type applications, to radically different systems and different timescales. Therefore, CPS emerge as a promising direction to enrich human to human, human to object and object to object interactions in the virtual as well as in the physical world.

CPS are complex at multiple temporal and spatial scales and are dynamically reorganizing and reconfiguring. CPS are globally virtual and locally physical and it will be required for the components to reflect characteristics and provide a unified view from local components to global systems;

When designing CPS, a practical approach is to consider three design layers, which include the physical layer, the network/platform layer, and the software layer. The physical layer represents physical components and their interactions, whose behaviour is governed by physical laws and is typically described in continuous time using ordinary differential equations. The network/platform layer represents the hardware side of CPS and includes the network architecture and computation platform that interacts with the physical components through sensors and actuators. The software layer represents the software components which are connected based on an input/output model implying a notion of causality [9].

4. TCAS IMPLEMENTATION AS A CPS

Collision avoidance algorithms establishing a collision-proof shield around each aircraft constitute a fundamental aspect of ACAS that will introduce a step change in future air transport. These algorithms need to provide resolution manoeuvres that guarantee collision avoidance while taking into account the constraints imposed by each aircraft performance and the requirements for reversal to human operators. To deal with the technical constraints of collision avoidance and aircraft performance, the implementation takes into account recent results from research in aviation, robotics, formal methods, and automatic control areas.

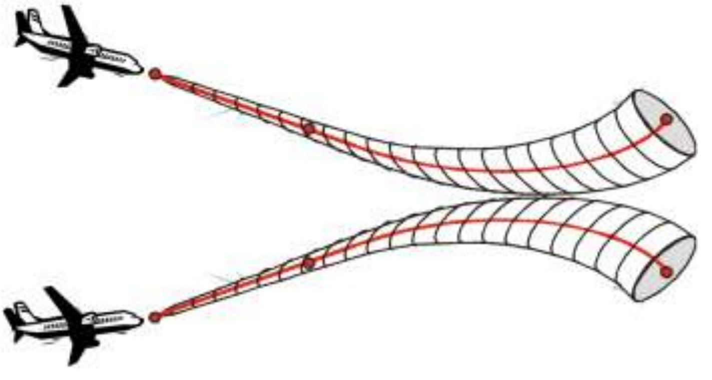

Fig. 5 – Auto-ACAS escape maneuvers with uncertainty

Bringing state-of-the-art methods from robotics and control theory into ACAS will enable the paradigm shift required to achieve much higher ACAS performance and enable much higher airspace density and diversity. Here we present the state-of-the-art in these areas and discuss how CPS research will go beyond it.

4.1 State-of-the-art in airborne collision avoidance via distributed control

A requirement for future ACAS designs is the drastic reduction (if possible elimination) of false alerts, to allow the collision avoidance automation and crew to focus on the real threats. False alerts are not uncommon in current ACAS and may cause pilot overload with undesired information, especially as the traffic density increases. In order to address this problem, [14] made use of control theoretic setting to develop a novel airborne collision avoidance algorithm. This algorithm requires a high level of coordination between the neighbouring aircrafts assuming a constant exchange of information. Apart from reducing "nuisance" this algorithm can handle asynchronous operation between the algorithms in different aircraft as well as delays that accumulate up to about 0.3s. This algorithm constantly evaluates a number of potential escape manoeuvres, taking into account the uncertainty of the aircraft's motion (Fig. 5). As long as there is at least one unobstructed escape manoeuvre, normal flight is maintained. When the last collision-free escape-manoeuvre approaches a collision, that escape manoeuvre is automatically executed.

4.2 State-of-the-art in Collision Avoidance in Robotics

We consider that future TCAS will make use of state-of-the-art robotics collision avoidance methodologies and formal methods which will bring a paradigm shift over the methods used so far in air transportation. Advances in those aspects will improve flight safety, and lead to higher traffic levels and more environmentally efficient flows. Potentially promising tools could be provided by research in Robot Navigation, a field that has addressed the collision avoidance issue during the last 3 decades. Various collision avoidance algorithms have emerged through this extensive research effort [32, 33, 34]. Many of them, however, are heuristic in nature and thus cannot guarantee a solution if it exists. This renders them inappropriate for airborne collision avoidance. TCAS focuses on robotic collision avoidance algorithms with provable performance and further develop and extend them to make them applicable to the ACAS design problem.

The Navigation Functions (NF) methodology is the main candidate methodology that we consider. Navigation functions have been introduced in Robotics as an evolution of the pioneering Artificial Potential Fields method in robot motion planning to guarantee a solution of the motion planning problem, if one exists. NF adaptations to address multi-agent scenarios have been applied to guarantee separation assurance in ATM in the previous EU projects HYBRIDGE [25] and iFLY [26]. Nevertheless, its application to collision avoidance as this needs to be investigated in more details. This is motivated in particular by the excellent applicability of the NF methodology to separation assurance [18] and will be a major part of the research for the years to come.

5. TECHNOLOGIES FOR ACAS IMPLEMENTATION AS CPS

For ITS, the main focus in research that is particularly related to CPS is connected vehicle technologies, specifically Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Examples of V2I applications include traffic signal violation warnings, stop sign violation warnings, pedestrian crossing information, and left turn assistance[14].

The latest efforts extend cooperative driving technology to road intersections, which involve issues that are more complex than lane changing and merging problems. For example, researchers have analysed how inter-vehicle peer-to-peer communications help vehicles near an intersection collaborate with each other. They view each vehicle as an individual agent and estimate the proper driving schedule through planning (and perhaps negotiation). Then they modify virtual-vehicle mapping and the trajectory planning method to handle the collision-free requirements and vehicle (dynamic and geometric) constraints. For example, one can imagine that each vehicle approaching the intersection transmits its movement information and driving plan to the repeater installed at the intersection’s centre. The repeater then transfers this information to other vehicles and to the network. Research along this path is slowed by different technologies available in different vehicles, but it could accelerate if automotive manufacturers agree on a communication protocol.

5.1 Intelligent Sensing for Cyber-Physical Smart Vehicles

Technology trends in consumer automobiles are moving toward increased autonomy. Early developments in -CPS for vehicles include traction and stability control, cruise control, and anti-lock braking systems that increase safety. Communication between vehicle components provides information such as velocity, acceleration, and traction for the purposes of navigation, infotainment, and other uses. These systems do not take control of the vehicle, but they provide information to the driver who ultimately makes a decision on how to act. Safety behaviours such as shaking the steering wheel to gain the driver‘s attention cannot alter the situation but can provide necessary information to the driver to enable action. Systems that perceive the environment outside the car as well as the environment inside the car are of particular importance. Three kinds of intelligent-vehicle sensing can be considered: out-of-vehicle environment, in-vehicle environment, and vehicle state sensing.

Out-of-vehicle environment sensing. This involves the process of collecting information about the driving environment outside. In particular, if we consider the road traffic, this include extracting lane boundaries, mainly when they are not clearly marked or in case of adverse weather conditions, detecting other vehicles that are nearby and estimating their position, speed, and acceleration; identification of traffic signs and traffic lights; detecting unexpected traffic partners like mocycles, pedestrians, etc.; sensing obstacles of all kinds. In aviation case things are similar, since we may consider the equivalent traffic neighbourhood (general aviation aircrafts, drones, balloons, etc.) and the orientation provided by radio controls on ground.

In general terms, sensing the environment out of the vehicle is a very challenging task, especially when we consider all weather operations. A lot of effort was spent in order to enable vision-based obstacle detection and traffic neighbours, but this is a difficult task. In case of road traffic, for example, pedestrians wear clothes in different styles and colours and may carry items such as bags, objects, or hats of different shapes. In addition, ambient illumination conditions (the sun hides behind the clouds for a moment) introduce distortions in the process. A solution to solve part of these problems is based on usage of images from multiple wavelengths sensors. Successful attempts used thermopile or infrared sensors and may fuse the images acquired from different sensors to increase robustness. All these technologies have been already introduced in aviation sector for military applications and are now ready for migration towards the civil sector. However, one cannot be 100% satisfied with the current status. Data obtained from the global positioning system (GPS) and cameras is often uncertain or even momentarily unavailable (in urban areas, for example). Current approaches combine GPS absolute localization data with data computed by a vision system to provide accurate vehicle position and orientation. Usually, one integrates the position and orientation data into a global reference using a map of the environment and then estimates localization parameters using a particle filter [15].

In-vehicle environment sensing. This involves mainly collecting basic information about the pilot/driver/operator, the passengers, cargo and on any target eligible for behaviour monitoring. If we focus on the pilot/driver, specific topics include monitoring the driver‘s eye movements, vigilance, and tiredness; the interaction inside the car; and so forth. This type of motorization has been extensively used in military applications and now is available as a standard option on most advanced vehicles.

At the same time sensing inside the vehicle is equally important to out-of-vehicle sensing. The pilot/operator/driver‘s diminishing vigilance level has become a serious problem in traffic safety and a major concern. A very efficient approach to this problem is based on the motorization of the driver‘s head position. This may be used to quantify the pilot/driver‘s fatigue level, mainly when this is combined with additional tracking technologies.

Vehicle-state sensing. This is in fact the basic approach in the development of the vehicle as a system and we may consider to be of a lower level of importance on certified vehicles. Globally this concentrates on characterization of the vehicle‘s movement and monitoring its actuators. Typical examples include velocity, acceleration, engine parameters, exhaust pressure and temperature, tire pressure, temperature, skin friction coefficients, detection of vehicle position and similar variables.

It is important to mention that there are different challenges in sensing out-of-vehicle and in-vehicle, manly when we consider external factors like illumination. The pilot can control the illumination environment inside the aircraft/car/vehicle, while the outside illumination environment is subject to the weather conditions and there is no possibility from the pilot to interact. The challenges for the inside car analysis are related to the analysis of human behavior and teams of engineers and psychologists are needed to address these problems in the future. Regarding out-of-vehicle sensing, the current trend of letting the sensors do the work, using sensing across the spectrum (e.g., infrared, thermal imaging) is useful but restricted by the difficulty of the motion segmentation problem. Specifically, the humans or other vehicles that will be detected are usually also moving. Several ambiguities can arise such that it is not possible to detect humans or other vehicles because of the special way in which they are moving. To address these issues, one would require an approach in which information fusion from a variety of sensors eliminates ambiguities.

5.2 Navigation Functions for Cyber-Physical Smart Vehicles

Navigation Functions (NF) are real valued maps realized through cost functions, the negated gradient fields of which are attractive towards the goal configuration and repulsive with respect to obstacles. Considering a trivial system described kinematically as:

$$\dot{q} = u \tag{1}$$

the basic idea behind navigation functions is to use a control law of the form:

$$u = -\nabla \phi(q) \tag{2}$$

where $\phi(q)$ is a navigation function to drive the system to its destination (Fig. 6).

It has been shown [27] that strict global navigation (i.e. with a globally attracting equilibrium state) is not possible and a smooth vector field on any sphere world which has a unique attractor must have at least as many saddles as obstacles. Further, navigation properties are invariant under diffeomorphisms; hence any world that can be diffeomorphically transformed to a sphere world can accept a navigation function [27, 28].

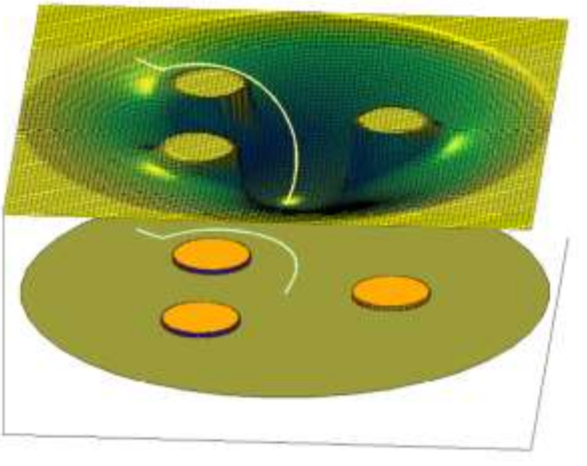

Fig. 6 – Navigation Function with three obstacles and the resulting gradient following path

Navigation Functions were initially proposed for single point robot navigation. Recent results [30, 31] allow application of the concept of Navigation Functions to navigation of multiple non-point robots via Multi-Robot Navigation Functions. Multi-Robot Navigation Functions have been developed for both centralized and decentralized [31] systems. There are several levels of decentralization, depending on the information available to each agent. The simplest form of decentralization is directly derived from the centralized case, where agents have full information and they calculate locally their control input. Intermediate levels of decentralization as in [29] assume full state information but only abstract information about the destinations of the other agents. Completely Decentralized Navigation Functions (DNF), assume only local knowledge of their neighbors and their environment as in [31, 30]. In those cases each agent calculates locally its control based on the positions of the neighboring agents. The navigation function serving as a Lyapunov function candidate used to prove stability for those decentralized cases is provided by the sum of each agent's DNF, resulting in an almost globally asymptotically stable system.

5.3 Human-in-the-Loop

A better understanding of human-cyber interaction is needed to incorporate human behaviour into models for these systems, if we would like to meet major goals defined by zero fatalities requirements. Incorporating human-in-the-loop considerations into the design and operational procedures is critical to dependability and predictability. The proposed new autonomous control systems will need to operate without fault alongside humans. Therefore we need measures and metrics to determine how safe this interaction will be, without sacrificing the benefits of autonomy [17].
It is also important to consider that even though there is a trend toward increasing autonomy in transportation, it is very important to ensure that human interaction remains a priority and to continue to keep humans involved (Fig. 7). In this approach humans play active and passive roles in transportation and have varying degrees of capabilities. Representing human behaviour in the design, development, and operation of CPS is thus a challenge.
Implementation of ACAS implies bringing of a new paradigm for human-centred full automation. Airborne collision avoidance with extremely high reliability can only be realized through guidance and control of the vehicle flight with very high or total automation. At all times, however, the pilot should maintain situation awareness, making it possible to revert operation to manual control. These human factors aspects need to be studied using the state-of-the-art in ecological human machine interfacing. The result is a new paradigm in human machine interaction that gives the real feeling of the implementation for proposed ACAS.

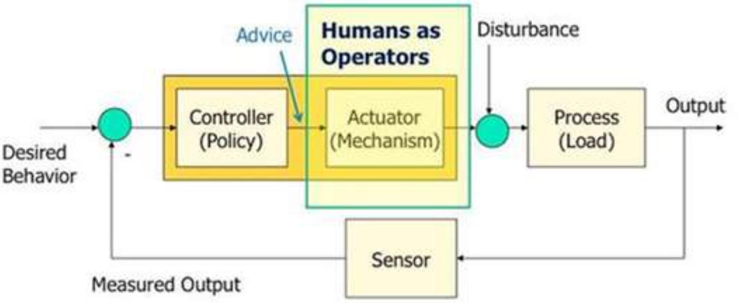

Fig. 7 – Human-in-the-Loop

5.4 Safety and Security

Safety is a paramount concern for any transportation system. As technology levels in vehicles drastically increase, the emphasis on safety and security must keep pace. One of the grand challenges to be achieved is zero fatality highways. It is expected that increased automation can help to achieve safety goals, but not without some challenges [18]. There is a possibility that integrated technologies will create more distractions for drivers, potentially causing safety issues. To ensure high levels of security for a highly integrated network, breakthroughs in security technology must be made that can be applied worldwide over various systems. As CPS become more complex and interactions between components increase, safety and security will continue to be of paramount importance.

5.5 T-CPS integration

A typical implementation scenario for T-CPS is presented for a collision avoidance case in road traffic conditions as existing on a future high speed road (fig. 8). To a certain extent, this is similar with proposed implementation scenario for aviation and TCAS.
Basic implementation infrastructure is using a monitoring and control surface network interconnected (wireless) to a global monitoring system and intelligent cars equipped with sensing technology and communication hardware. The observer in the monitoring center may have either an active or a passive role, depending on the level of requested interaction.
The basic scenario is triggered by an unexpected event (obstacle) requesting a quick response from the car in front of the obstacle to stop. This event will generate a perturbation in the traffic with the potential to end in a massive collision, mainly due to incoming cars not able to avoid contact with the stopped car, or due to the need for a sudden change of lane, also leading to potential collision with other cars in the traffic.

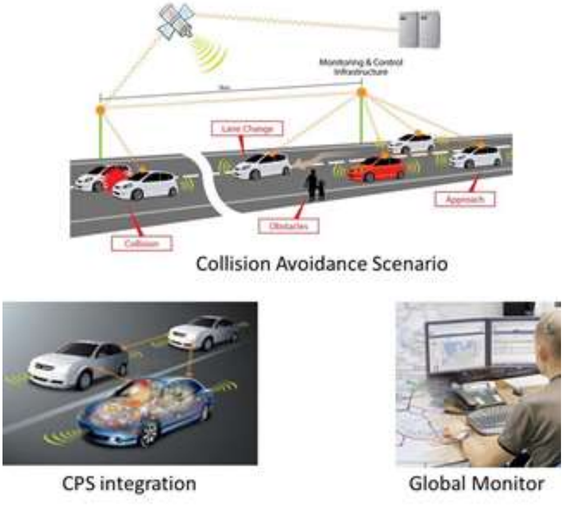

Fig. 8 – T-CPS implementation scenario – Road Traffic Case

CPS integration into the vehicles and also the smart road infrastructure should prove that, once the system activated, approaching cars are informed well in advance and provided with the needed information for the trajectories to follow so that the collision is avoided. Also, the incident is reported to the global monitoring centre where higher level decisions may be triggered, possible with the assistance from the human supervisor. At system level all interconnected fluxes will be informed and global traffic is redirected for the duration of the perturbation event.

6. ACAS SIMULATION FOR CPS

A proposed T-CPS simulation environment is proposed based on current state-of-the-art tools available for CPS. A comprehensive survey for such tools dedicated to road traffic is available from Wagh, Hou et.all [19], where ATS is an open access traffic simulation package developed using Visual C++ (http://atsimu.sourceforge.net/). The implementation uses the environment provided by Zhengbing [20]. It is able to reproduce thousands of vehicles, which can be treated or set as agents, running on a designed network; There are multi-lane links, intersections with vehicle conflicts, traffic signals, simulated loop detectors and guidance boards. Vehicles can move following different traffic flow models, like cellular automata (NaSch) or car-following Gipps models. The vehicle trajectory, N-curve, and latest macroscopic fundamental diagram (MFD) can be collected and the platform has the ability to communicate with other systems. For ACAS implementation for aviation applications there is an equivalent simulation platform with a very advanced aircraft simulation environment provided by D-SIX. The algorithms may be implemented in c-code and integrated in a non-linear 6 DOF equations software flight simulators.

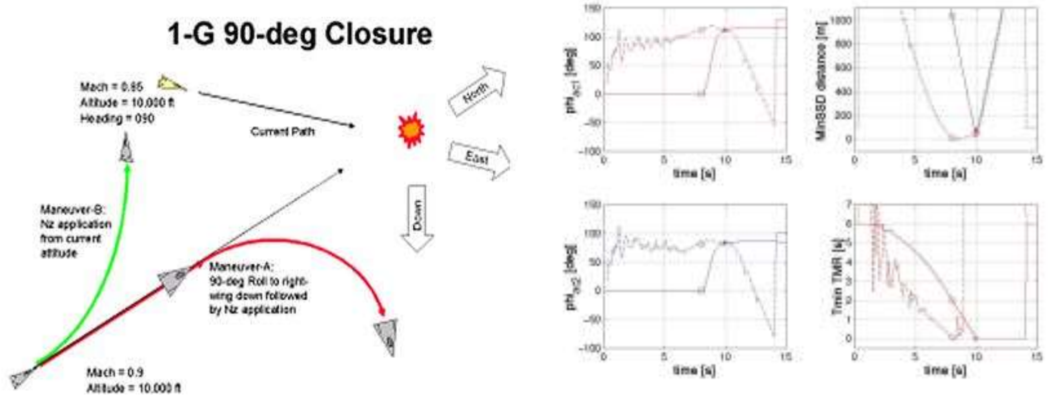

Fig. 9 – ACAS scenario simulation in D-SIX environment

The basic assumption in a typical simulation scenario is based on the reality that advanced aircrafts include a data link for air-to-air and air-to-ground communication and a basic electronic flight control system (FCS) which is at the heart of the system and used for executing the avoidance manoeuvres. The ACAS algorithm may be implemented by software changes only in the FCS, under the data link triggering control. This is the minimum requirement to qualify an aircraft as a CPS. The standard approach is to use algorithms that will prevent collision based on predicted probable trajectories. Instead, in this simulation we introduce the ACAS algorithm that claims space along a predicted escape trajectory (time tagged positions were the aircraft will be after an avoidance is executed) which the aircraft will use in the case an avoidance manoeuvre is necessary and this will be used as a standard implementation. The major benefit we expect from using the escape trajectory in this implementation is that we can be predicted with greater accuracy the probable trajectory which the aircraft will follow if no avoidance is executed. A flight dynamics model for the aircraft is loaded in D-SIX. Then the escape trajectory is executed in a predetermined way by the ACAS algorithm using the FCS, whereas the probable trajectory is affected by the change in pilot commands. The size of the claimed space is computed using knowledge of the wingspan, navigation uncertainty and accuracy of the predicted trajectory compared to the one the FCS will make the aircraft follow if the escape command is given. Based on the specific implementation of the flight dynamics model integrated in D-SIX, each aircraft sends its predicted escape manoeuvre and the size of the claimed space along this track to the other aircraft, using the data link. All aircraft will use the escape manoeuvres from the different aircraft to detect a future lack of escape, as in fig. 5 and fig. 9. If the distance between the escape trajectories is greater than the safety distance imposed by the regulations and/or team leader, the track is stored as the one to use in case of avoidance. Else the avoidance is executed using the FCS to make the aircraft follow the stored trajectory. The basic scenario implemented is related on the head-on collision trajectory, as in fig.9. Due to various interferences, one may assume that a GPS positioning error, data dropouts and/or delays in controls may lead to a collision.

Embedded ACAS algorithm has been tested for a typical scenario involving two aircraft on head-on collision course, both at same altitude and at different high Mach speeds, as in fig. 9. ACAS variables (bank angle, earth fixed absolute evasion angle, actual distance between the aircrafts, MinSSD - shortest distance between the claimed spaces, Tmin – time when the shortest distance between the claimed spaces would occur and TMR – estimated time remaining until the algorithm will activate its manoeuvre) during head-on scenario are presented, with the collision estimated at T=10s. In the simulation, the aircraft heading north performs a roll to +112 deg, the other to +82 deg. The evasion starts when the distance is 1075 meters and lasts for t=2.1 seconds, resulting in a missed distance of 72 meters.

The current implementation of the algorithm gives reliable, predictable results both in low and high dynamic scenarios. From the simulations performed we could not observed any nuisance when aircraft was operating outside the safety zones currently used in the normal EASA procedures, and activations were performed only in cases where collisions would be unavoidable. We conclude that ACAS algorithm is generic in the sense that it can accommodate different aerial vehicles such as commercial aircrafts, fighters, UAVs, drones, etc. with a minimum of aircraft specific adaptation. Any aircraft that has the capability to compute/predict its avoidance trajectory at least 5 seconds ahead and has the capability to communicate that information via a data link, can be protected with ACAS.

7. CONCLUSIONS

CPS are engineered systems that are built from and depend upon the synergy of computational and physical components. Emerging CPS will be coordinated, distributed, and connected, and must be robust and responsive. The CPS of tomorrow will need to far exceed the systems of today in capability, adaptability, resiliency, safety, security, and usability.

Cyber Physical Systems for Transport System (T-CPS) is a new conceptual development for future ITS based on the synergy of the following:

- Cyber Physical Systems (CPS) concept
- Multimodal Transport System concept
- Smart Mobility & ITS concept

Current development status for T – CPS is focused on a vehicle cooperative control framework based on the coordination between individual vehicles as well as between vehicles and the transport infrastructure, where vehicles' efficiency can be improved in a vehicle cooperative framework controlled by a multimodal traffic management system. This is under investigation in the simulation environment described.

CPS provides the technology to be embedded in the vehicles and the infrastructure in order to enable a T-CPS environment able meet the new standards for safety, resilience and efficiency as imposed by Smart Mobility. As described above, for the ACAS design the expected impact value of the novel value analysis methodology is to be demonstrated through its application to the Pioneering-ACAS design. This will show that this innovative method is able to identify the various potential development paths for future economic scenarios. This may seem trivial, but it is not. The reason is that in aviation industry a novel safety directed technology typically can be used for other purposes than just improving safety. For example, ACAS is able to provide a much higher safety gain than current TCAS does, then there are multiple options how this potentially may be used in practice. Increased levels of automation also have a significant link to potential reductions in cost on the one hand, and increased revenue generation on the other due to increased capacity and efficiency. Example options are:

• Using the ACAS design simply to improve the safety of civil aviation;

• Using a large improvement of the last resort safety net for the benefit of air traffic capacity, rather than improving aviation safety.

• Using a large improvement of the last resort safety net for the benefit of reducing environmental pollution.

• Equipping novel air vehicles with the advanced last resort safety net in order to guarantee that they do not potentially harm any of the TCAS equipped aircraft.

• Adopting a specific combination of the above four options, in order to realize a balanced improvement on safety, on capacity and on environment.

As presented in the T-CPS simulation environment, the issues raised by the implementation of a true ITS are serious, but should not be considered an insurmountable barrier. Challenges related to non-technical factors can be overcome by experts in other fields, such as the judiciary, business or political environment, and their expertise would complement the skills of engineers and scientists who create these new technologies.

Problems related to future transport technologies to solve their sizes in the areas of legal, institutional, social, environment and economy. Research should also cover longer a complementary planning of a new technology developed. It is necessary to widen the attention attributed to these practical needs, only this can advance the current state of ITS technologies from special small-scale initiatives to global universal applications.

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