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ETHICAL BEHAVIOUR OF AUTONOMOUS NON-MILITARY CYBER-PHYSICAL SYSTEMS

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Abstract.

Autonomous non-military cyber-physical systems are widely studied in research but there are still few applications in industry. One of the reasons relies in the fact that there is still no proof of guarantee for these systems regarding their safety and their ability to behave in a nonhazardous way, mainly because of the induced complexity caused by their learning abilities coupled with the high ability to interact and cooperate of their composing mechatronics elements. More, cyber-physical systems are intended to be merged into socio-technical systems and interact with humans. As a consequence, the study of their ethical behavior translates currently a major stake. Meanwhile, it is clear that this stake is still not address by the scientific community while 1) sci-fi literature and movies have addressed this since a long time 2) some autonomous road vehicles have already injured people, and 3) EU parliament has launched a procedure dealing with the establishment of civil laws for autonomous learning robots. This paper intends then to open the debate on this topic and suggests to extend dependability studies to integrate ethicality as a new dimension. New emerging research fields are identified and an illustration in the autonomous train transportation is presented.

Introduction

Cyber-physical systems (CPS) are complex systems aiming to fulfill a global function and integrating communicating mechatronic parts, sensors and effectors, merging the physical and the digital worlds [1]. They interact with human operators. In our work, we consider a sub-class of CPS, more complex, that are autonomous. In this paper, autonomy refers to the ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve goals [2]. These CPS can thus behave and evolve in space independently neither from the decision of a human operator nor the one of its designer. They can integrate Artificial Intelligence-based learning mechanisms enabling them to improve their decisions with time and adapt to an evolving environment [3]. The CPS concerned in this paper are also non military: their primary function is neither concerned with the destruction of asset nor people, like one can find in the military or defense industries [4].

This paper, co-written by a lawyer specialized in the domain of digital property and cyber-security and a researcher working in the field of industrial internet and CPS, deals with the ethical behaviour of this kind of autonomous non military CPS¹. The will of the authors is to foster researchers working on

¹ For simplification purpose, we will no more precise “autonomous and non military” in the remaining of the paper when using the acronym “CPS”.

this kind of CPS to pay attention to the possible consequences of their design on the welfare of humans interacting with these CPS such as their possible responsibility in case of an accident.

Futuristic non-scientific ideas more relevant to entertainment and sci-fi than science have initially put the light on this subject (as illustrated by Asimov's robotic laws, Mary Shelley's creature, Philip K. Dick short stories, etc.). Meanwhile, this subject became reality and went to the public place since the worldwide discussed recent case of the Tesla self-driving car crash that led to death [5].

As introduced, the scope of the paper concerns Ethics. Ethics is initially a field of philosophy. According to [6], ethical behaviour is concerned with actions that are in accord with cultural expectations relating to morality and fairness. Ethical aspects in engineering is not new and some journals are specialized in that field [7]. These aspects have been studied in various fields of engineering, such as design [8] and obviously bio-engineering, including genetics [9]. In the literature, one can face two kinds of ethical studies [3]:

- techno/engineering ethics that deals with the moral behaviour of human designing artificial beings (the issue being the **ethical design of CPS**), and
- machine ethics that deals with the moral behaviour of artificial beings (the issue being the **design of ethical CPS**).

In a previous paper, a review in ethical aspects in complex system engineering has been made [3]. Main conclusions are provided hereinafter.

Regarding techno ethics, proposals were mainly fostering the adoption of techno ethics behaviours by researchers related to the idea of charters to be signed ("Hippocratic oath").

In this paper, since we deal with the ethical behavior of CPS, our work is rather related to machine ethics. Regarding this field, it is worth noticing that main breakthroughs are coming from lawyers. Starting from the point that there exists a huge corpus of "human being centered" laws, while quite none dealing with "artificial beings", lawyers have started to pay attention to robotics and artificial intelligence (AI). One of their surprising approaches is to consider the creation of a new specie composed of intelligent autonomous robots and systems, aside the human one. This approach implies that human right constitutions should be revised accordingly. For example, [10] discussed the organization of administrative control and the legal liability regime which applies to service robots and the issue of autonomy of service robots. Another example, which is from the authors' point of view, among the most amazing studies, is currently led at the European Union (EU) Parliament level that worked on legal proposals related to robotics and AI [11]. Apart from the recommendations' main goals, which are devoted to human safety, privacy, integrity, dignity and autonomy, the EU Parliament aims to unify and incentivise European innovation in the area of robotics and AI. According to these recommendations, the definition of a **smart autonomous robot** (SAR) has been proposed: a SAR acquires autonomy through sensors and/or by exchanging data with its environment (inter-connectivity) and trades and analyses data; It is self-learning (optional criterion); It has a physical support; It adapts its behaviours and actions to its environment². Following their idea, different categories of SAR would be created. It is advised that a specific legal status for robots is created, so that at least the most sophisticated SAR could be established as having the status of electronic persons. A SAR would also have rights (intellectual property and personal data...) and obligations (a SAR should be held reliable for its actions according to the EU Parliament, which asserts that "the greater a robot's learning capability or autonomy is, the lower other parties' responsibility should be, and the longer a robot's 'education' has lasted, the greater the responsibility of its 'teacher' should be"). The concept of SAR is obviously close to the one relevant to the kind of CPS we consider in this paper. Meanwhile, only few works dealing explicitly, from a scientific point of view, with machine ethics in SAR/CPS are available [3]. Among them, let us mention [12] who proposed a framework for assessment and attribution of responsibility based on a classification of CPS with respect to the amount of autonomy and automation involved. Their proposal is based on the assumptions

² It is clear that what EU calls a SAR is very close to that what is called a CPS in this paper.

that different types of decision making occur inside a CPS: automatic, semi-automatic, semi-autonomous and autonomous decisions.

Provided the important stakes introduced about the emergence of machine ethics issues in CPS on the one side, and the lack of research activity from the scientific community, far behind the activity led in the legal field on the other side, the aim of this paper is to promote the emergence of a new field of scientific research: *the ethical behavior of autonomous, non-military CPS*.

To contribute to such an ambitious objective, our idea is to start from scientific theoretical grounds that can be considered as the closest to this new field and to extend this field to encompass machine ethics in CPS engineering. From this perspective, one of the closest research fields that was found and that is discussed in this paper concerns the “dependability analysis” for which recent studies on autonomous systems and robots are already available [13]. Of course, this does not forbid machine ethics in CPS engineering to gain also from other fields such as AI (multi-agent systems, artificial neural networks, etc.), mobile robotics, embedded/mechatronics systems, etc.

The next part summarizes the terminology from the historical field of dependability and points out the angle of attack through which machine ethics may foster the generalization of dependability to encompass ethical aspects. Applications and illustrations will be taken from the transportation sector, whatever the mode (aeronautical, naval and ground transportation), the emergence of autonomous systems in this field, and especially the Google Car, being a clear illustration of where our society is going to.

1 Dependability analysis: RAMS studies

Even if the word is known for years by researchers, there is no real consensual precise definition of dependability. For example, in the norm IEC 60300-1, dependability is defined as “the collective term used to describe an operation based on the availability and the influential factors: reliability, capacity and support to the maintenance” [14]. It is commonly accepted by researchers that dependability is composed of three main parameters: reliability, maintainability and availability aside which one fourth parameter is more and more added: safety. The acronyms RAM and RAMS (along with the relevant term “RAMS studies”) are usually used by researchers working on dependability.

It is beyond the scope of this paper to discuss the definition of these parameters, the relative literature being abundant. Thus, adapted from [14], the chosen definitions used in this paper for illustration purpose are the following:

- **Reliability:** the ability that a system operates satisfactorily during a determined period of time and in specific conditions of use. It can be expressed as a mean time to failure (MTTF).
- **Maintainability:** the capacity of a system to be maintained, where maintenance is the series of actions taken to restore an element to, or maintain it in, an effective operating state. It can be expressed as a mean time to repair (MTTR).
- **Availability:** the ability to perform when called upon and in certain surroundings. It can be expressed as a percentage: the proportion of time a system in a functioning condition over a given time period.
- **Safety:** the ability to detect undesired events and to apply rules to limit (mitigate) their consequence.

More recently, **Security** has also been added as a fifth parameters. Security is the ability to operate satisfactorily despite intentional external aggressions. In that sense, Security is related to external events while reliability, internal events.

Obviously, Safety and Security are the closest indicators relevant to ethical aspects but one can see that they do not consider all the aspects relevant to ethics. From our point of view, safety and security must then be studied with a wider view, as discussed in the following part.

2 Dependability of CPS: from RAMS to RAME studies

The idea that we defend in this paper is that it seems possible to enlarge the safety/security aspects of RAMS studies towards machine ethics as a federating, more global concept encompassing safety and security. According to this idea, we suggest that RAMS becomes now RAME: Reliability, Availability, Maintainability and **Ethicality**. From our point of view and in this paper, *ethicality refers to the ability for a system to behave according to an ethical manner*. The core question is obviously what is an “ethical manner”. The following section deals with such an aspect.

2.1 Ethicality and ethical behavior of a CPS

As introduced, safety and security can be seen as components, yet to be adapted, of ethicality since from our perspective, ethicality is a more global concept, enlarging the fields of research founded on these two components. One can notice that the discussed elements hereinafter present some links with Azimov’s laws of robotics. It is also noticeable that the components described hereinafter are under the responsibility of the designer of CPS if these CPS are “simple” in the sense that all of their states and behaviors are clearly identified, bounded, controlled, certified. Meanwhile, the responsibility of a CPS can be engaged as soon as it becomes autonomous and able to learn, and the more it learns, the less the responsibility of the designed is committed, consistently with the previous discussion about the legal responsibilities of a SAR.

These components are described hereinafter.

A first component of ethicality is **integrity**, that is the ability to behave so that the others trust the information coming from the CPS and are confident about the ability of the CPS to engage actions to reach a clear, readable, public objective (even potentially varying), but which must be announced and publicized in that case. This includes for sure the ability for the CPS not to disclose sensible information gathered about the humans and other CPS interacting with it. The designer of the CPS is highly responsible for this (ethical design), but the CPS will be the one that risks to disclose sensible information when it takes decisions in an autonomous way, or it is the one that may change its objectives with no explanation, which influences the degree of trust from the humans, then its ethicality. Integrity includes also the ability to verify the algorithms by others and to trace (explain) the decisions. For this aspect, a common current solution is to implement open (no black box), certified, checkable-by-others computer codes, but this is not sufficient since the CPS must also be able to explain its choices (for example, when investigating to determine the root cause of an accident for which the CPS was involved).

Safety is a second component of ethicality. As already introduced, safety concerns people involved and in direct connection to the considered CPS. Ensuring that a system behaves in a safe way, limiting the risk of injuries to human beings that depend on the CPS is the least that one could accept to determine if a CPS behaves ethically. For example, energy providers must provide their nuclear plant with procedures and rules to limit as much as possible hazardous events for employers and close urban areas. A cobot system, aimed to work jointly with a human operator, owns barriers and safety rules to avoid harming human operators (eg., torque or effort detection). But from an ethical point of view, this is not so simple. A typical emerging ethical issue at this level would concern the kind of decisions that could maintain the safety of the CPS while at the same time, that could be harmful for people. For example, a safe decision for an autonomous high-speed train that detects lately an animal on the track could be to brake to avoid the collision while at the same time, it risks to hurt several of its 1,000 passengers, the ones that are at this moment not seated, with this emergency brake.

A third component of ethicality is **security**. Security refers to the resilience of the CPS facing unexpected aggressive actions. It concerns the ability of a CPS to limit its vulnerability and intrusion, cyber-attacks and aggressive behaviors (threats) coming from systems and events not only outside but also inside the CPS, which is a new aspect induced by the principle of ethicality. Regarding outside threat,

cyber defense (firewalls, anti-malware, etc.) are of course among the most famous approaches studied by industrialists and researchers. Regarding inside threat, and from a machine ethic point of view, this component becomes delicate to address. For example, should the auto pilot of a plane be able to override the command of a human pilot if it may lead to crash the plane (eg., suicide) ? if yes, how to ensure that this override may not lead to a more critical situation (eg., difficulty for the cruise CPS to land the plane) ? It is noticeable that security and integrity may be conflictual component: increasing the integrity by using open source AI code may facilitate the work of cyber-attackers, thus reducing the security of the CPS.

Altruism (or caring) is a fourth component of ethicality and one of its ultimate components. It has never been addressed by researchers in the field of CPS. Altruism can be seen as a complementary view of safety. Altruism is more aligned with the welfare of people a priori not interacting with the CPS, while safety focuses on the people interacting with the CPS. It concerns the ability to behave according to the welfare of others: others being other technical systems, other CPS or human beings. Altruism may be also contradictory to one or several of the other components and RAM indicators. For example, an altruist autonomous boat, that detects a "SOS" message, delays its current mission to help the senders of the SOS. But through this altruist decision, it will de facto reduce its availability (its mission may be canceled) and this decision may impact its reliability as well (overuse of its turbines used at full throttle to reach as soon as possible the emitter of the SOS for example). Another example is the one of an autonomous car that has to break the law in order to save life (eg., emergency trip to hospital, line cross to avoid a pedestrian, etc.) [15], reducing its accountability (see below). Of course, reducing the accountability, the reliability or the availability is not a necessary condition to behave in an altruist way. For example, an altruist autonomous train detects an accident on a road close to its track (fire, smoke...) and makes an emergency call to its central operator while continuing its travel to its destination at the same time. Its mission is thus not impacted.

Accountability (or liability) is another one of the ultimate components of ethicality. Accountability ensures that actions led by the CPS engage its responsibility in case of a problem. Being quite a futuristic idea, like altruism, when dealing with non-human based systems, this is an important aspect promoted by the EU through its legal proposal previously introduced. If a CPS is accountable, then in case of hazard, its legal responsibility could be engaged, leading to allocating insurance funds to injured people. The CPS could be sued for that hazardous behavior. Telling people that the autonomous train they are using is covered by the insurance of the train itself, for which it contributes through the payment of a tax coming from its own earned money render this CPS as a new accountable entity, belonging to a new specie, aside the human one.

Equitability (financial fairness) is also another ultimate component of ethicality. It ensures that if the CPS becomes an artificial, accountable person able to spend money for insurance (accountability), then, as a counter balance, it must be able to earn money. This must be done in an equitable (fair) way, with a balanced repartition of the money earned through its use to ensure its ethical behavior. This component translates a logical evolution of the previously introduced legal developments related to SAR since SAR and CPS are artificial beings potentially able to create and generate knowledge, ideas and to improve their performances compared to other SAR. This process should increase the competitiveness of a CPS, make it gain customers. For example, an autonomous train, known to behave more ethically compared to a competitor train may attract more customers. Gaining market shares means earning more money.

Fig. 1. From RAMS studies to RAME studies summarizes this evolution from RAMS to RAME studies where (E)thicality is decomposed into the previous listed components. In this figure an intuitive dichotomy, splitting ethicality into two levels is represented. The first level represents the immediate research activity needed to be started. The second level addresses the more elaborated, complicated, delicate to imagine components of ethicality. From our perspective, the second level can not be reached until the first one is sufficiently elaborated.

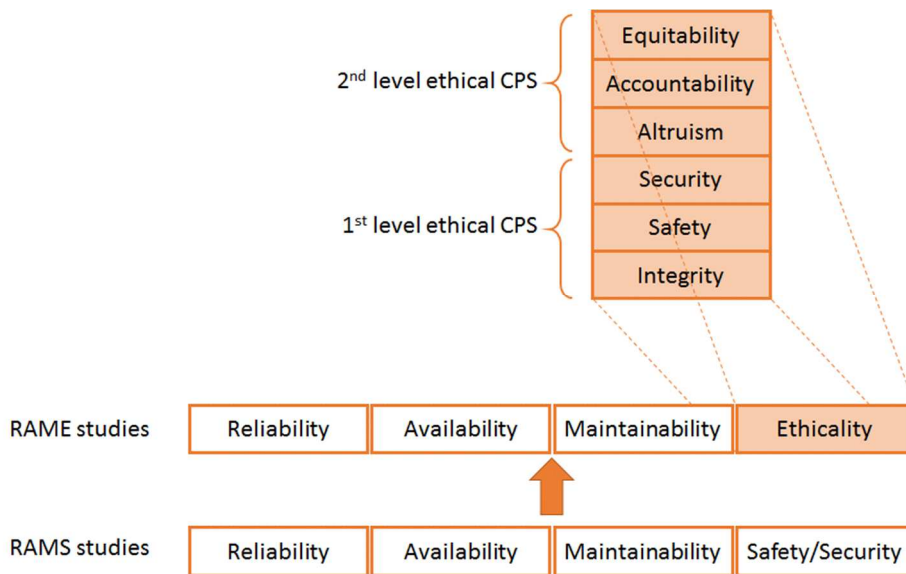


Fig. 1. From RAMS studies to RAME studies of CPS.

2.2 Some key relevant issues in RAME studies of CPS

From this definition of ethicality, one can identify a large number of issues. We list hereinafter some of the most challenging ones for illustration purpose:

- To ensure an ethical behavior, a first reflex would be to design rules to force artificially the ethical behavior of a CPS. For example, "when driving, priority is gradually set first to animals, then trucks, then pedestrians, then bikes, then motorbikes, then cars, then buses". But an ethical behavior is still a complex concept to formalize, and defining in an exhaustive and sense full way all possible ethical rules seems an insurmountable task up to now.
- As introduced, these different components of ethicality are conflictual, that means that improving one may lead to the degradation of another one (ex., improving altruism may degrade safety, improving integrity may degrade security, etc.).
- Deciding which decision is more ethical than another is sometimes a delicate choice to make. The classical "Trolley problem", which translates a "no-win" situation where each possible choice (and especially, inaction), leads to the death of one or several people, is a clear illustration of this.
- Linked to the previous issue, modeling an ethical behavior, optimizing it and simulating situations to evaluate the degree of ethicality over a short or long time horizon will be a strong issue as well. Measuring such a degree and stating that "system1 behaves more ethically than system2 during this amount of time" seems to be quite impossible to do with the current scientific state of the art.
- Last, the corpus of current laws is described in a textual way. This will not be possible to use a similar approach to define legal rules and laws for CPS. Thus, the co-development by lawyers and scientific searchers of ethical rules applicable both to the human and the artificial beings becomes a key issue. This could be done using mathematical, formal or algorithmic editions of laws and social rules to be embedded into CPS, which is a necessary condition to make them behave ethically.

To summarize, evolving from RAMS studies to RAME studies of CPS becomes a challenging, really new field of researchers for scientists and it is time for our community to appropriate this field. For sure, everything has to be done. The intention of this paper is only to draw the attention upon this urgent

need. New theories have to be invented, new models defined, new indicators and new methods as well. But this is not sci-fi. The google car obviously forces us to address this and each other of the transportation modes is becoming affected by this evolution. Major industrialists and operators are working on the autonomous train, the autonomous plane, the autonomous tractor, the autonomous ship, etc. As an illustration of this, the next part details an application to train transportation.

3 Application to train transportation

Future autonomous trains are clearly the kind of the CPS considered in this article, and will be thus concerned with ethicality. The evolution of the development of “classical trains” towards “autonomous CPS-train” is governed by several driving factors. The first one is obviously related to the limitation of crashes and accidents through a better monitoring of the train and its environment. A second one concerns the possibility through the use of autonomous trains to increase the number of trains used per time unit, thus the number of passengers. Indeed, the capacity of the infrastructure, which represents a large amount of money involved, can not be easily augmented. To augment the number of people transported, the solution offered by the autonomous train is to increase the number of trains by reducing the time between two trains on a track and by adopting train pooling-like systems only controllable using advanced AI technologies. The use of a similar approach for fret transportation, on long distances, would also limit the use of conductors on tiring, long trips. Last, energy is an important driver. This concerns not only energy savings during a travel, but also the consensual limitation of the energy peak used inside a fleet of autonomous trains based on negotiations among these trains to organize the smoothing of the energy used. Estimated relevant gains are huge.

We describe hereinafter two complementary activities to illustrate the ongoing search for the future autonomous train and provide some insights about RAME studies concerning it.

The first illustrative activity concerns a major national project led by the French national railway agency, SNCF, who is working to implement the « autonomous train » in few years. This “EFIA” project is thus a meta-project aiming to define the future development projects and target fleets of trains. It is managed by a technological research institute (IRT), Railenium. Railenium is defining the roadmap towards the “autonomous train” and specifies the deployment process, including the future applied projects to launch, accompanied with a methodological support to develop them in collaboration with industrial and academic partners.

The second illustrative activity concerns a joint research laboratory, called the SurferLab³, which is a joint research laboratory with Bombardier Transport, Prosyst (a French SME) and the university of Valenciennes and Hainaut Cambrésis in France. It aims to develop models, methods and systems enabling the embedding of intelligent self-prognostic and health management functionalities into train, rendering this train more autonomous, able to actively self-diagnose and thus, to actively negotiate with maintenance centers and other trains of the fleet to optimize the quality of the fleet service.

The obvious conjunction of these two different activities clearly illustrates the will of the railway sector to work on the autonomous train (the Deutsche Bahn also works on this topic [16]). For the moment, and consistently with our previous discussion about the sequential addressing of the two levels of ethicality, these two activities consider only the first level of ethicality: integrity, safety and security. From discussions with industrialists in train transportation and researcher in autonomous systems, dependability and AI, even these first components are hard to address assuming an autonomous behavior of the CPS-train. For example, homologation of train requires to proof some safety levels (SIL). This is feasible through a complete edition of all possible situations by engineers for “classical” non autonomous trains, but when train starts to learn and behave autonomously, this is no more possible. That means that even

³ www.surferlab.fr

homologation rules must evolve as well. In addition, these two activities even don't pay attention to altruism, accountability and equitability. Industrial partners acknowledge that they must be studied in the near future as well, but they do not know how to address this.

4 Conclusion and future works

It is estimated that in the USA 94% of the car crashes are due to driver errors [17]. This kind of statistics fosters the development of autonomous, self-learning CPS. One of the key issue to solve in the near future is relevant to the ethical behavior of these systems interacting with humans and evolving in crowded environments. Ensuring the ethical behavior of designers does not mean that the designed system will behave ethically. This paper opens the debate on the crucial and urgent need to deal with this issue. There is up to now nearly no scientific contribution on this topic while lawyers have started to work on it since several years. Defining ethicality, modeling it and ensuring it, is for the moment quite impossible to do. This means that researchers face now full, open and really new scientific research fields yet to explore within the context of RAME studies.

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