Natural and Manmade Shared-Control Systems: An Overview

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Abstract
In this paper, natural and manmade-shared control system examples are presented. Analogies and differences among these systems are discussed. Then, basic requirements for successful cooperation in shared-control systems are identified. Finally, an ambitious general framework for human-machine shared control is proposed. Here, only intelligent machines that would otherwise function autonomously are considered.

1. Introduction
The last 30 years have witnessed a dramatic increase in the number of intelligent autonomous machine applications. These cover a wide spectrum ranging from very sophisticated systems like the autopilot of passenger airplanes through intelligent vehicles to pet robots. Most of these systems are designed to improve the performance of, or assist, human users in different tasks. However, the unstructured, unpredictable, hostile, and dynamically varying environments make it imperative in certain cases to make use of distinguished human decision-making capabilities. Moreover, as all these technologies are meant to be “human centered,” then it is expected that the human user is required to intervene in supervising and controlling such systems. A control framework is therefore needed to facilitate the sharing of control between a human user and an intelligent machine (or an intelligent agent) taking advantage of the unique strengths of the human and the agent and aiding each other in those areas of weaknesses.

Recently, some excellent works have been dedicated to shared-control issues. Sawaragi et. al., [1] applied Vicente’s idea of ecological interface design to a mobile robot teleoperation system. A method for integrating the human-robot interaction into the task plan is suggested in [2]. Aigner et. al., adopt discrete event system theory to model human interaction and further to integrate a human supervisor into an otherwise autonomous system [3]. In more general terms, issues of human interaction with automation are discussed in [4,5].

A unified general approach, or at least guidelines, to design and implement an intelligent shared-control system is, however, still missing. As humans have been always tempted to mimic natural phenomena and systems, this article is a contribution in this direction. Namely, we try to state the basic requirements and to identify technical tools for shared-control system design based on our observations of natural systems.

2. Natural shared-control systems
In this section, cooperation examples in the nature are given. Forms and tools of interaction among the intelligent agents are analyzed.

2.1 Animal-animal interaction
In the animal kingdom, almost all species tend to have different cooperation behaviors in daily life activities like protection, foraging, and grooming. Different reasons for cooperation are identified [6] to include kin selection, reciprocal altruism, and mutualism. Cooperating animals must be able to coordinate their activities by means of some type of a communication system. Formally defined, communication is an action on the part of one animal that alters the behavior of a second animal. Channels of communication can be chemical, visual, auditory, or tactile as observed by mammals. It is noticed [6] that is more the rule than the exception that several communication channels are integrated. This provides an adaptive type of redundancy and enables certain animals to produce a relatively great range of signals.

Different types of signals are reported [6,7] to be utilized in animal communication. These can be classified as specific versus general, where specific signals are more complex and more expensive in terms of energy consumed and may take longer to broadcast. They evolve when there is a strong advantage associated with the specificity. Another classification is discrete versus graded; discrete signals are signals that are either present or absent where a graded signal is variable and its variations convey information about the level of the sender’s motivation. Generally, the higher the level of motivation the more intense the signal and the longer its duration. Graded signals are most likely to be used when there is interaction between individuals. Mammals and birds are more likely to use graded signals in their communication than ectotherms.
Regarding communication displays; it has been established [6] that it is not true that animals that communicate large amounts of information must use a large variety of displays. This can be explained by the existence of enrichment devices. Enrichment can be achieved by:
- Medley: where two or more signals are present at the same time.
- Regulating the intensity or duration of display.
- Contextual effect: where the context in which a signal is given can enrich the message.

Redundancy, on the other hand, is a common tool. It can be achieved by the repetition of the signal or by the presentation of two signals or more with same meaning at the same time. It increases the probability that a message will be received correctly. Repeated communication may enable the animals to periodically reassess or restate the immediate situation. Moreover, it is noted that redundancy enhances memorability in certain cases.

2.2 Human-animal interaction

Whereas ethology relies merely on scientific observations in studying animal behavior, here introspection and self-questioning serve as legitimate analysis tools. A good traceable example of human-animal shared control and interaction is horseback riding [8].

Task sharing is well organized; the horse usually takes care of all low-level tasks such as coordination of leg motions, stability, avoiding obstacles, and providing enough power and speed for different actions. On the other hand, the human rider provides the global planning and may take care of other activities as in a polo match. Moreover, the rider interacts with the horse to fulfill tasks, and can override any of the horse’s behaviors when necessary.

The rider, seen as a system, is completely autonomous as she has adequate perceptual, cognitive, and motoric abilities. The horse, on the other hand, can be seen in a similar light. Although its cognition is limited, it could perform all related tasks autonomously. It can at least wander without any external help. In the case of horseback riding, both parties give up some of their responsibilities. The rider relies on the horse’s motoric abilities and the horse’s behavior becomes more intelligent by complying with the rider’s commands to achieve a wonderful human-animal cooperation. The interaction between the two happens in a simple and natural way. The rider commands the horse via the reins, leg pressure at the saddle girth, and by applying and shifting pressure on the seat. The horse interacts with the rider by applying forces upon her through its neck and by rearing up on its hind legs (in case of a dangerous obstacle as a snake).

It is believed [8] that the horse acknowledges the rider’s commands if they exceed a certain threshold. This threshold depends on the horse’s training, on who is riding (age, maturity, etc), and on the current state of the environment. The rider corrects and overrides the horse’s behavior by increasing the level of stimulus (pulling the reins more, pushing harder on the saddle, or increasing the frequency of an action). This continues until the horse changes its behavior as wished by the rider. A lack of proper interaction in show jumping, for example, can end with funny or dangerous scenes.

Both memorization and reinforcement learning or operant conditioning apply for the rider and the horse in establishing effective coordination and communication protocols. However, the rider can take advantage of more advanced learning methods like supervised learning [9]. An “intelligent” horse can learn and master a set of rider patterns and changes its behavior in accordance with its identification of the rider.

2.3 Human-human interaction

The daily human life is rich of human-human cooperation tasks that involve control sharing such as when two children play on the seesaw, two or more persons lift a heavy or a big object, assemble a complicated device, or synchronize actions in a given setup, and other activities that include direct physical contact.

The choice of communication signals and displays made by individuals for a given task is adaptive and subject to the proficiency level of the participants. For example, a kindergarten teacher may speak to communicate with a child who sits on the seesaw for the first time. Later on, children rely on reflexive forces and gesture recognition to negotiate a playing strategy. However, they may be forced to communicate verbally to resolve a conflict before mastering the game.

In a shared-control task, humans tend to change their behavior and communication protocols depending on the proficiency of the partner. Moreover, they continuously monitor the behavior of the partner and identify his/her intentions and even his/her physiological state. Accordingly, they may adjust their participation share in the process (lifting objects), tune their speed (assembling devices), or even warn their partner verbally of some danger and sometimes take over the process completely.

In summary, the main features of human-human interaction are the dynamic choice of communication tools, the adaptation to the competency of the partner, and the continuous monitoring of the partner. Thus, the cooperation and interaction strategy is selected in a closed-loop control fashion. Rasmussen [10] proposed some models of cognitive control in cooperation and interaction tasks. These models include skill-based, rule-based, knowledge-based control and the shifts among them.

2.4 Conjoined-twins interaction

The most impressive natural control sharing is that of conjoined twins. For example, each of the Hensel twins, Abigail and Brittany, has her own heart and stomach, but
together they rely on three lungs. Their spines join at the pelvis, and below the waist they have the organs of a single person. Each controls the limbs and trunk, and feels sensations, on her side exclusively; if you tickle the ribs on the right, only Abby giggles [11]. Although, they have two brains and two minds, the girls manage to walk, run, and swim. No one knows exactly how they can coordinate their actions to move as one being. However, it seems this became possible as their spines are joined at one point.

The famous Siamese twins, Eng and Chang, became the subject of many psychological studies. Even in literature resources from the nineteenth century, one can find remarks denoting shared-control behaviors like “it appears that each twin in rotation became passive when it was his brother’s turn to be active.... the twins devised this technique for insuring a form of alternating autonomy and that Judge Graves refers to the surrendering of the will that was necessary to allow it to function” and “with Chang paralyzed in both an arm and leg, it must have been quite taxing on Eng to compensate for his twin’s impaired mobility” [12].

3.2 Telerobotics
Teleoperation permits humans to maneuver robots from a distance. Thus, a human’s ability to intelligently manipulate and inspect can be performed in an otherwise inaccessible or hazardous environment. To increase the accuracy and the reliability of teleoperation, close interaction between the human and the slave robot is required. Many force feedback devices and control architectures have been investigated for this purpose. Usually, the communication link between the human and the robot’s location is bandwidth limited and has time-varying delays. This also limits the fidelity with which the human can intervene in the remote environment.

Recently, some works have been dedicated to shared-control issues in telerobotics. A method, that relies on transforming the task from the workspace into a configuration space, for augmenting the human performance in teleoperation tasks is proposed by Ivanisevic [13]. This method aims at making the human and the robot act as partners rather than master and slave; the human employs the ability to see the big picture and to quickly assess changes in the environment while the robot relies on machine intelligence in spatial reasoning for example. A similar approach, that is based on model-based supervisory control, is proposed by Ho et. al. [14] to reduce human attendance. There, the human operator delegates some of the control tasks to the robot through a set of high-level commands in contrast to the classical moment-to-moment manual feedback control.

3.3 Autopilots
Most of the commercial airplanes and many private airplanes are provided with autopilot systems. Some of these systems are capable of choosing the flight route, navigating in all weather and sight conditions, taking off, and landing. Although there is not much space for conflicts and conflict resolution, a fine pilot-autopilot cooperation and interaction is required. It has been pointed out that incomplete pilot’s declarative or procedural knowledge of the autopilot can lead to fatal human errors [15]. Accordingly, a set of suggestions has been made to augment the performance of the pilot and to enhance his trust in his automated partner, see [15] for a review.

3.4 Intelligent vehicles
The future projections of current technological advancements and trends indicate that a motor vehicle will become a complex mobile computer. Three main areas of vehicle intelligence are: route guidance systems to help drivers navigate unfamiliar streets, collision avoidance systems to prevent accidents caused by delayed driver’s response, and in-vehicle automation systems that can temporarily take over driving during emergencies or allow autopiloting for prolonged durations. The driver’s role expands then from that of a sensory-motor skill to that of a planner, programmer, monitor of the automation, diagnostician, learner, and manager [16]. Although technologies in the vehicle can enhance the driver’s capabilities and comfort, they can also create potential distractions that transform even the best driver into a road hazard.

An intelligent vehicle initiative was launched in the USA to develop a human-centered transportation system [17]. Such a system must specifically address how information will be managed and displayed, how technologies can be improved to better serve drivers, and how drivers can learn to operate intelligent vehicles safely and effectively. As
drivers will have access to more information than they are traditionally accustomed, the vehicle itself must do some information filtering or data fusion. The study [17] addresses, as well, points mentioned in previous sections of this paper like: media by which messages are conveyed to the driver (text displays, speech, bells and whistles), how humans best understand and process information, how drivers understand how to use such a technology. However, what the study does not touch on is how to avoid or resolve conflicts in a real time and how to make the vehicle “understand” the intentions behind the driver’s action.

3.5 Autonomous manufacturing
The last two decades have witnessed a clear shift in manufacturing technologies. Computer integrated manufacturing (CIM) was followed by intelligent manufacturing systems (IMS) to handle the integration of the increasing number of intelligent manufacturing components. Recently, holonic manufacturing systems (HMS) are introduced. Such systems are constructed of autonomous, cooperative modules called holons. A holon is defined as an identifiable part of a whole system that has a unique identity. HMS regards the elements of manufacturing systems, such as machines and human operators, and even the manufactured products as holons. One key feature in holonic manufacturing systems is flexible human integration [18]. The background for this is that human intelligence is superior whenever unexpected or complicated situations are met.

Furthermore, and in a recent study, one of 10 technology areas selected as the most important for meeting the grand challenges for manufacturing in 2020 is enhanced human-machine interfaces [19]. The study affirms that interfaces must include all appropriate media. Ideally, interfaces will be adaptive and customizable (i.e., they will be able to improve communications with specific individuals as they use the interfaces). Seamless human input technologies could include a range of topics, from voice synthesis and control to full sensory input to direct mind-machine interfaces. Research on man-machine interfaces could include remote control for globally distributed enterprises, technologies that simplify and display large amounts of process data, interfaces that compensate for physical disabilities, and "smart" process algorithms. Research on learning and design processes that will enhance worker performance include neural networks learning theories, decision support tools that are integrated with manufacturing operations and equipment, new techniques in education and cognitive science, training with simulations/virtual reality, and situation theory [19].

4. Common features of shared-control systems
It is worth mentioning here that shared control is a subset of cooperation. In cooperation, it is possible that more than one agent cooperate to do a job without having to share control over a process. On the other hand, in share control, the agents can simultaneously control (energy and command flow) a common process. Based on the examples and review given in the previous two sections, the following features are extracted to be favorable for a successful shared-control system:

- Agents communicate their perceptions, states, and intentions.
- Agents support multi channel communication and redundant messages.
- Agents adapt, modify, and negotiate their communication protocols and behaviors depending on the proficiency of their partners.
- Agents continuously monitor the behavior of partners.
- Agents sense and memorize novel stimuli.
- Agents characterize their partners based on their behaviors.
- Agents can cooperate and interact with different partners with different proficiency levels.
- Agents learn as a result of cooperation and interaction.
- Agents can resolve conflicts with partners flexibly and dynamically.

As we are concerned with the subcategory of man-machine shared-control systems, the above features can be reformulated. First, an intelligent machine continuously and repeatedly displays to the user in an effective and maybe a redundant style an idea about its perception, internal state, and intention. Second, as users or partners can have varying perceptual, cognitive, and physical capabilities, the machine adapts its behavior including its communication tools in accordance. Third, to be able to do that, the machine monitors the behavior of the partner and builds and updates a model for that partner. Fourth, as the cooperation environment is dynamic and as the partner may undergo different moods, the machine adjusts its level of involvement and resolves any arising conflicts.

5. Requirements and tools
In this section, we elaborate on the four requirements mentioned above and we identify some technical tools to satisfy those requirements.

5.1 Communication
Depending on the machine and the nature of application, the human partner should get necessary information about the machine’s perception (how it sees the environment), internal state (mode of operation / uncertainties / difficulties), and intention (selected action strategy and tactic). Moreover, it displays what it “thinks” about the human partner (you are tired, you don’t understand me, you have difficulties, you are cooperating nicely...). The communication signals and displays should be as natural as possible, i.e. in the forms of natural speech, full texts, visual signals, virtual reality, or reflexive forces.
However, all of that should be decided dynamically by the machine depending on observed proficiency level of the human partner. The amount of spoken information can decrease as the human partner becomes used to the cooperation. As discussed in the animal-animal interaction section, enrichment tools can be employed to have a better communication with few displays. Graded signals should be used to indicate the strength or the importance of the message.

As all humans have limited and constrained perceptual capabilities, the machine should not overwhelm the partner with huge amounts of information and displays. Novel stimuli can be always saved to critical situations when it becomes a must to attract partner’s attention. Guidelines for ergonomic communication and displays are well established in the human-factors literature, see [20-21] for details.

5.2 Human’s behavior monitoring
The most important requirement for an intelligent man-machine shared-control system is that the machine monitors the behavior and the state of the human partner. Without this, none of the other requirements like adapting machine’s communication or behavior can be fulfilled. It is not imaginable that two humans can share control over a task without having the means to monitor each other’s behavior. Moreover, it does not suffice, in most cases, to speculate about that behavior by evaluating its impact on the environment.

In applications where the human commands the machine directly (e.g. intelligent vehicle, autopilot, telerobotics, wheelchairs), the machine has a direct access to, at least a part of, the human’s behavior. More information about the physiological state of the human partner can be gained through special sensors that can be mounted ergonomically between the human and the machine. These include blood pressure, pulse rate, skin humidity, and even human body pressure distribution sensors [22]. Such information can be further fused to formulate metrics of excitement, tiredness, and satisfaction for example. On the other hand, when the human doesn’t command the machine directly (e.g. mounting a car’s door with the help of a robot, holonic manufacturing), then it becomes imperative for the machine to rely on reflexive forces, gesture recognition, speech recognition, and maybe on analyzing body motions.

Based on the sensed state of the environment, on any previous knowledge on the particular human, and on any available combination of those information discussed in the previous paragraph, the machine processes the data to figure out the following:

1. Human’s action: what is the partner doing?
2. Human’s intention: what is the partner trying to achieve?
3. Human’s state and mood.
4. Human’s model: modify any available model or establish a model entailing cognitive, character, and skill parts. As this cannot be a general model, it must be confined with the shared task under consideration.

A machine capable of achieving this can be classified as cognitive. The process of transforming the available information into the above four outputs is an active area of research in the artificial intelligence field. Some promising methods and tools that have been successfully implemented are:

- Bayes classifier with sequential probability revision [22],
- Cascade neural networks [23],
- Partially-observable Markov decision problems [24],
- Hidden Markov models [25-26], and possibly
- Inductive logic programming [27].

5.3 Machine’s behavior adaptation
Based on the processed outputs, the machine dynamically selects a strategy to deal with the human partner given a particular task in a certain environment. This covers:

- Communication: amount and level of displayed information as discussed in a previous section.
- Level and type of involvement and collaboration: to account for any variations in the human’s activity, proficiency, and mood. An intelligent partner should care for the goals and interests of its partner and go beyond his/her delegation and request. But only cognitive partners can safely cooperate beyond delegation [28].

5.4 Conflict resolution
Since partners in a shared-control system usually perceive the environment differently and as their knowledge, cognition, and intelligence vary; then conflicts and contradictions in intentions and actions are anticipated. As a human-machine shared-control system resembles a cooperative rather than a competitive interaction, conflicts can be resolved on the long run by better communication between the interacting partners. However, a shared-control framework must have a conflict resolution unit in the form of an arbitration strategy. Different arbitration methods for reactive systems are given in [29]. In general, solutions can be found in the framework of:

- Decision fusion and decision theory.
- Utility functions and theory.
- Game theory

6. Concluding Remarks
In this article some important issues of designing a human-machine shared-control system are addressed. An ambitious framework and design tools are proposed. The role of adaptive communication is highlighted.
7. References


