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Title: Matching brain-machine interface performance to space applications

Running title: Matching BMI performance to space applications

Authors: Luca Citi, Oliver Tonet, Martina Marinelli

Corresponding author: Oliver Tonet

Affiliations:

Luca Citi
Department of Computing and Electonic Systems
University of Essex
Wivenhoe Park, Colchester, CO4 3SQ, UK
email: lciti@essex.ac.uk
Telephone: +44-1206-87-3291
Fax: +44-1206-87-2788

Oliver Tonet
NOT AFFILIATED TO ANY INSTITUTION FOR THIS PAPER
Address:
European Patent Office, Room S05B24
Patentlaan 2, 2288EE Rijswijk, The Netherlands
email: otonet@epo.org
Telephone: +31-70-340-2317
Fax: +31-70-340-3987

Martina Marinelli
Scuola Superiore Sant'Anna
piazza Martiri della Libertà 33, 56127 Pisa, Italy
email: m.marinelli@sssup.it
Telephone: +39-050-315-2819
Fax: +39-050-315-2166

ABSTRACT

A brain-machine interface (BMI) is a particular class of human-machine interface (HMI). BMIs have so far been studied mostly as a communication means for people who have little or no voluntary control of muscle activity. For able-bodied users, such as astronauts, a BMI would only be practical if conceived as an augmenting interface. A method is presented for pointing out effective combinations of HMIs and applications of robotics and automation to space. Latency and throughput are selected as performance measures for a hybrid bionic system (HBS), i.e. the combination of a user, a device and a HMI. We classify and briefly describe HMIs and space applications and then compare the performance of classes of interfaces with the requirements of classes of applications, both in terms of latency and throughput. Regions of overlap correspond to effective combinations. Devices requiring simpler control, such as a rover, a robotic camera, or environmental controls are suitable to be driven by means of BMI technology. Free flyers and other devices with six degrees of freedom can be controlled, but only at low interactivity levels. More demanding applications require conventional interfaces, though they could be controlled by BMIs once the same levels of performance as currently recorded in animal experiments are attained. Robotic arms and manipulators could be the next frontier for non-invasive BMIs. Integrating smart controllers in HBSs could improve interactivity and boost the use of BMI technology in space applications.

Keywords: Brain–computer interface; Brain–machine interface; Latency; Space; Throughput.

I. Introduction

Advances in technology allowed mankind to build machines which are used to interact with the environment in our stead, when direct action is not possible or not desirable. This interaction is mediated by a Human-Machine Interface (HMI).

From a control system viewpoint interacting with a HMI implies translating intention into motor commands, dispatch them toward the target muscles and translate the results of the action, collected through the sensing system, into feedback for the central nervous system (CNS). A brain-machine interface (BMI) allows to break this loop by translating a person's intentions directly into commands to a device. Some BMIs bypass the musculo-skeletal system completely, allowing severely disabled people, who have no voluntary control of muscles, to communicate (Wolpaw et al., 2002; Donoghue, 2002; Mussa-Ivaldi and Miller, 2003). However, to date no technology can provide a viable feedback method by directly stimulating the CNS and therefore the usual approach is to use the natural senses, such as vision or touch, in order to dispatch relevant information to the brain. Information transfer rates of BMIs are low, if compared to conventional HMIs: even the most skilled BMI typewriters can write only few letters per minute.

Nevertheless, able-bodied people can still benefit from BMIs, if they are designed as augmenting interfaces, i.e. interfaces allowing them to perform actions in addition to what they already can do with their normal abilities. It is precisely in this scenario that BMIs can be gainfully applied for space applications: astronauts are able-bodied and specially-trained people, it would therefore make little sense for them to avoid using conventional interfaces, such as keyboards and joysticks, in favour of BMIs, which currently require a high cognitive load, are affected by artefact signals from other activities, and offer a poor information transfer rate. Only if astronauts or technical people from Earth will be able to use BMIs together with conventional interfaces, or to achieve some goals for which conventional interfaces are not suitable, it will make sense to introduce BMIs into space applications. This is why we believe that, for space applications, augmenting interfaces will have a dominant role.

In this chapter we hypothesize that performance of HMIs can be roughly compared independently from task, method, and user. After describing HMIs and devices for space applications in terms of latency and throughput, which are used as performance measures, we match the requirements of devices with the performance of available interfaces in order to point out effective combinations.

II. Methods: performance measures of HBSs

The ensemble user-interface-device, comprising both artificial and biological components, is defined as Hybrid Bionic System (HBS). A number of parameters and of definitions of the same have been used to characterize performance of HBSs (Kronegg et al., 2005). In this chapter we will adopt throughput and latency as performance measures.

Throughput (also called bit rate, bandwidth, or information transfer rate) is the amount of data that is transferred over a period of time and is measured in bit/s. Latency is a time delay between the moment something is initiated, and the moment one of its effects begins (onset latency) or reaches the azimuth/nadir (peak latency).

In the following, classes of interfaces and devices are characterized. For each class, a numeric range for throughput and latency is defined. Throughput of devices (TP_d) was calculated as the product of the number of bits per unit command b (in bit/command) and the number of commands per second ν (commands/s) that have to be sent to the device to be able to control it interactively:

$$TP_d = b\nu.$$

The throughput of interfaces (TP_i) has been calculated as the Shannon information rate in (Shannon, 1948). This definition of throughput is also popular in the literature on BCIs, having been first suggested by Wolpaw et al. (1998). In a number of BMI papers TP_i is not reported; however, the number of symbols, the error probability and the transfer rate (symbols/s) is stated or can be inferred. In calculating TP_i, a symmetric N-symbol channel with symbol rate R and error probability (1 − P) has been hypothesized:

$$TP_i = R\ (\ lg_2\ N + P\ lg_2\ P + (1 - P)\ lg_2\ ((1 - P)/(N - 1))\ ).$$

The value of latency is usually reported or deducible from the description of the experimental protocol used to generate the physiological signal measured by the interface. The minimum value of latency is limited by physiological characteristics of the neural fibres and relays forming the control loop, by response times of the musculo-skeletal and sensory systems, by how interactive the system is designed to be, and by how much feedback is needed to close the control loop. Latency is also bound by the time resolution of the technique used to measure the user's intent or action.

Throughput and latency were chosen as initial measures for determining whether a given interface and device are suitable to be integrated in a HBS. Among the numerous factors that can be pinpointed, they are probably the only ones easily quantifiable and comparable. Therefore they seem a reasonable choice in order to perform a first selection allowing to individuate which combinations of interfaces and devices are in principle possible and which ones are surely not.

Other important factors, albeit beyond the scope of this chapter, need further to be considered for the final design of the HBS, such as degree of invasiveness, user-friendliness, portability, set-up time, need for training, cost/effectiveness balance, robustness to noise, instantaneous and cumulative cognitive load required, temporal stability, etc.

III. Materials

III.A. Brain-machine interfaces

The performance of BMIs presented in this chapter is based on data collected from a number of studies. These studies include all the papers considered in (Tonet et al., 2008) plus a number of additional and more recent articles[1]. BMIs have been grouped according to their type, as shown in Fig.1, first into cortical interfaces, which exploit information collected from the central nervous system, and non-cortical interfaces, in which the information is measured at the peripheral level, and further as explained below.

[Figure 1 about here]

In *cortical non-invasive interfaces* (C-NI), brain signals are recorded from the scalp and are attenuated by their transit through the extracerebral layers. This group comprises interfaces based on different types of brain signals: event-related potentials (ERP) and event-related (de)synchronisation (ERD/ERS) related to motor imagery, to different mental states or to

1 For the sake of brevity we refer to (Tonet et al 2008) for the list of papers already considered in that work. In addition we also used data from recent papers by Acharya et al. (2008), Achtman et al. (2007), Bai et al. (2008), Bell et al. (2008), Brychta et al. (2007), Farina et al. (2007), Hoffmann et al. (2008), Karim et al. (2006), Krepki et al. (2007), Momen et al. (2007), Müller-Putz et al. (2008), Müller-Putz and Pfurtscheller (2008), Nijboer et al. (2008), Pham et al. (2005), Shenoy et al. (2008), and Truccolo et al. (2008).

imagined sensory stimulation; P300 evoked potentials, generated by mental selection of items arranged in a sequence or into square matrices; slow cortical potentials (SCP) and sensorimotor cortex rhythms, related to 1-D and 2-D movement tasks; steady-state visual evoked potentials (SSVEP), related to 1-D movement tasks and nominal selection of targets.

Cortical invasive interfaces (C-I) are characterized by a higher sensitivity than non-invasive ones because they are able to detect directly the voluntary firing of individual neurons in the primary motor cortex. During experiments with primates, the signal recorded has been related to complex 3-D movement tasks. So far, during experiment with human subjects, only signals related to 1-D or 2-D movement tasks and to nominal selection of up four mental states have been recorded.

In *non-cortical invasive interfaces* (NC-I), signals are measured directly from the peripheral nervous system by means of implantable electrodes. Finally, *non-cortical non-invasive interfaces* (NC-NI) comprise conventional interfaces (e.g. switch-based interfaces, pointing devices, and speech recognition) and interfaces based on electromyographic (EMG) signals.

III.B. Robotics and automation for space applications

To protect human beings from the hazard of the hostile environment outside the Earth atmosphere, in manned space flights astronauts have been enclosed in vehicles (for intra-vehicular activities) or special suits (for extra-vehicular activities, EVAs) (Hirzinger et al., 2000). As a complement and alternative, robotics and automation (R&A) is now one of the most attractive areas in space technology, allowing to develop machines that are capable of surviving the rigours of the space environment, performing some activities like exploration and assembly, reducing EVAs and occasionally improving performance over humans performing the same tasks. They can be sent into situations that are so risky that humans would not be allowed to go (Wilcox et al., 2006).

For the purpose of this study, robots for space applications have been grouped into the following categories.

Rover robots are vehicles launched by a lander over a planet or a satellite for exploring them and for characterizing soils and rocks. Though the size of rovers can range from larger vehicles for EVA to smaller autonomous vehicles, they share 3 degrees of freedom (DOF), 2 translational and 1 rotational. EVA rovers are interactive, whereas remote rovers, depending on the time delay, can be teleoperated or be embedded with sensors for autonomous movement control.

Manipulator robots are teleoperated robot arms which are useful to deploy or retrieve payloads or satellites on a space craft or station, for assistance in EVA activities such as assembling, maintenance, and repair, and, provided with cameras, as inspection aids. Typical manipulator robots have a complexity comparable with the human arm, though their size can range up to tens of meters, and are teleoperated at an interactive rate by a human operator located on the same space craft or station.

An *"astronaut-equivalent" robot* is designed specifically to work with and around humans. The robot's considerable mechanical dexterity allows it to use tools and manipulate flexible materials much like a human astronaut would. Moreover, space suits often do not allow astronauts free dexterous movements, a limitation which could be overcome by using an astronaut-equivalent robot. The considerable complexity of these robots, which can have more than 50 DOFs, regarding hardware and control systems makes them suitable only for local teleoperation. To simplify the HMI, their parts (e.g. head, arm, hand, leg or trunk) may be controlled individually.

Free flyers or free floating robots are robots launched in space and able to move in 6 DOFs, 3 translational and 3 rotational. Their usage scenarios are similar to that of space rovers, i.e. inspection and characterization of the atmosphere of planets or satellites. Their higher complexity requires accordingly more complex commands. The base unit may be additionally provided with manipulators for performing dexterous operations.

An additional application of R&A to space flight is *environmental control*, i.e. the application of domotics to space, for monitoring of the environmental parameters inside a spaceship or space station.

Three key issues have been considered to express the performance of devices for space applications in terms of throughput and latency: first, *mobility*, i.e. moving quickly and accurately between two points without collisions and without risk to the robots, humans and the work site; second, *manipulation*, i.e. using dexterous robots to manipulate objects safely, accurately, and quickly, without accidentally contacting unintended objects or imparting excessive forces beyond those needed for the task; third, *time delay*, i.e. allowing a human operator to effectively command a robot to do useful work. The operator may control the robot from a "local" console, e.g. an astronaut inside the pressurized cabin of a space craft, or from a "remote" console, e.g. a human operator on Earth, with non-negligible speed-of-light communication delay with the robot.

The requirements, in terms of throughput and latency, of the above space applications have been estimated from data contained in the following studies: (Kim et al., 1992), (Sheridan, 1993), (Peñín et al., 2000), (Miller and Machulis, 2005), (Wilcox et al., 2006).

Concerning throughput, we computed the throughput as the product of the number of bits per unit command and the number of commands per second that have to be sent to the device to be able to control it directly, as in a master-slave system, and interactively. This is a conservative estimate, since shared control methods can reduce the need for bandwidth: this issue is discussed in Section V below. Also, we do not consider here the bandwidth necessary for operator feedback, typically visual feedback, which, though being a considerable consumer of bandwidth, does not affect the suitability of an interface for a given application.

Similarly, the value of latency for space applications was considered to be the acceptable time interval from the user's intention to the moment the command is received by the device, neglecting the return time needed for feedback. Therefore, only half of the round-trip time reported in the above experiments was considered. For space applications where no literature data was available, requirements have been estimated taking into account related applications, such as ultrasound-based deep ocean teleoperation (Sheridan, 1993) and rehabilitation (Tonet et al., 2006). By slowing down the speed of devices and implementing autonomous control schemes, there is theoretically no upper limit to latency. However, the reported values take into account the maximum time allowed for a typical task, e.g. a payload positioning task should be completed in minutes, not hours.

IV. Results: matching interfaces and devices

In this section the performance of the interfaces described in Section III.A are matched with the needs of the applications presented in Section III.B. Identifying the regions of overlap allows to define realistically which applications could in principle be driven by means of a given BMI and also which types of BMI could be suitable for a given application. As said, this matching represents a necessary, but not sufficient, condition and other factors must be considered in the final design of a HBS.

Figure 2 shows the overlap of application needs (rectangles) and interface performance (convex hulls). Figure 3 is similar, but the different HMIs are grouped according to invasiveness (invasive/non-invasive) and to the location of the hybrid link (cortical/non-cortical).

[Figure 2 about here]

[Figure 3 about here]

At a first glance, it can be pointed out that applications that require little throughput and tolerate higher latency could be driven by any of the interfaces considered. These applications comprise devices for environmental control, an astronaut-equivalent head, and rovers. In the next section we will present three possible demonstrators of BMI-controlled space applications. Furthermore, to some extent, control of free flyers and of an astronaut-equivalent leg is also possible by means of several separate interfaces in all four groups, even though for some interfaces the overlap is limited to the lower part of the required throughput range.

The requirements of more demanding devices, namely the manipulator arm and the astronaut-equivalent hand, are met only by conventional interfaces. Also an EMG-based interface could allow some form of control of an astronaut-equivalent hand, probably a smart underactuated one requiring less throughput than conventional robotic hands. The same could apply to invasive cortical interfaces, once the performance of human subjects reaches the one obtained by monkeys. In fact, performance measured in monkeys suggest that cortical invasive interfaces could be used successfully for controlling prosthetic hands with greater interactivity. However, with cortical invasive interfaces, humans have not reached the same performance as monkeys. In (Hochberg et al., 2006), the quadriplegic human subject that received the 96-multi-electrode array was able to control a computer cursor to interact with home appliances, operate the opening and closing of a prosthetic hand, and perform rudimentary actions with a multi-jointed robot arm. It is worth noting that he could perform these actions even while conversing, which suggests that invasive interfaces have greater capabilities of discriminating shared output, i.e. simultaneous orders of different content, than non-invasive ones.

Complex compound devices, namely the astronaut-equivalent arm and the whole astronaut-equivalent robot, require performance that is currently not attained by any of the interfaces. While the latency requirement is well accomplished by a few interfaces - invasive ones, conventional ones, and EMG - the limiting factor is the throughput. In fact, the control of a robot with many independent degrees of freedom requires an overall throughput well above the capabilities of the state-of-the-art interfaces.

V. Possible demonstrators

Based on the regions of overlap between the performance of interfaces and requirements of applications in Fig. 2 and 3, a few demonstrators can be envisaged. Three of them are briefly described and discussed in order to verify their feasibility beyond the mere numerical comparison of throughput and latency shown in Fig. 2 and 3.

A first demonstrator migrates the concept of domotics to space applications. Several BMIs are suitable for operating environmental controls. This result is not surprising: indeed, the control panel of domotic applications is usually a simple interface composed of switches and sliders, controls that are easily implemented by means of a BMI (Gao et al., 2003; Cincotti et al., 2006). Nevertheless they should not be the first choice. It is obvious that mechanical buttons and sliders, or their equivalent on a graphical user interface, are the most intuitive way to toggle switches or set ranges. Nevertheless, EEG-based BMIs have sufficient throughput and acceptable latency to be used for demonstrating BMI-based environmental control.

A second demonstrator is a hands-free control of two DOFs. Practical scenarios include steering of a camera (e.g. a rover-mounted camera, the astronaut-equivalent head) while the user's hands are controlling robotic manipulators, by means of joysticks or exoskeletons, for ground exploration or spaceship maintenance. This application shares many aspects with interfaces allowing an impaired user to scroll the screen and reach icons and widgets on a computer desktop (Citi et al., 2008). A related application, namely 2-DOF cursor control and map navigation on a computer display by means of a dependent BMI that requires change of the gaze fixation point, has been recently investigated at NASA by Trejo et al. (2006). If, while using the BMI to control 2 DOFs, the user was able to use his hands to control additional interfaces, this would be an *augmenting application*, i.e. an application that could not be performed in the same way by one person alone. However, further investigation is required to rule out that the use of the BMI concurrently with traditional HMIs is made impossible by an excessive cognitive load or by interferences between the mental activity related to the BMI and the one related to the task at hand.

A third demonstrator is a direct porting of an existing rehabilitation device, namely a BMI-driven wheelchair, to a space application, by substituting the wheelchair with a space rover. BMIs may not be the best choice for driving a rover: conventional interfaces, such as a joystick, yield better results with almost no training and user fatigue at all. Nevertheless, brain activity recorded non-invasively is sufficient to control a robot moving on a surface, especially if the devices embodies some smart high-level controller (Tanaka et al., 2005; Galán et al., 2008).

In this regard, concerning complete HBSs in which the interface part has lower performance than required by the application, it is possible to overcome limitations of the interface by improving the effectiveness of the commands sent to the device, i.e. by developing smart high-level controllers, which are able to perform parts of the tasks autonomously (Sheridan, 1993). HBSs with low-level controllers and no autonomous behaviour will leave all decisions to the users and will require many simple commands to be driven interactively. The commands will be simple (few bit/command) but frequent (many commands/s). On the other hand, an embedded high-level controller with a high degree of autonomy will accept complex commands from the user and then act autonomously, typically in a closed feedback loop based on data read from internal sensors. Such a controller will require complex commands from the user (many bit/command) but less often (few commands/s). Controllers with a modular degree of autonomy allow the user to switch between lower and higher levels of control, ensuring that the user is always in control of the device, but freeing them from the burden of controlling it continuously. Modulating degrees of autonomy could also be a means to overcome gaps between interface performance and application needs, by developing more deeply integrated HBS.

VI. Conclusions

In this chapter a method to match interfaces and devices to form hybrid bionic systems has been presented and possible space applications have been pointed out. Though the main focus is on BMI applications, the method is applicable to all kinds of HMIs and can be used in general to determine, for a given application, what interface is best suited to control it. It can also be used conversely, to find the applications that are most suited for a newly developed interface. Throughput and latency were selected as measures, since they are defined on all kinds of devices and interfaces and can easily be computed or estimated. Besides them, other variables affect performance of HBSs and need to be taken into account for the development of a complete system. Especially in the case of space applications, the different performance of the human component of the HBS cannot be neglected.

Results show that devices requiring simpler control are suitable to be driven by means of BMI technology. Devices with many degrees of freedom can be controlled at the cost of suboptimal interactivity. More demanding applications require conventional interfaces, though they could be controlled by BMIs once the same levels of performance as currently recorded in animal experiments are attained. Integrating smart controllers in HBSs could boost the use of BMI technology in space applications.

In conclusion, it appears as the future of research in HBSs will have many facets: not only there is room for improvement in all their individual components (user, device, interface), but also for developing more efficient strategies to make those components interact (control).

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Figures:

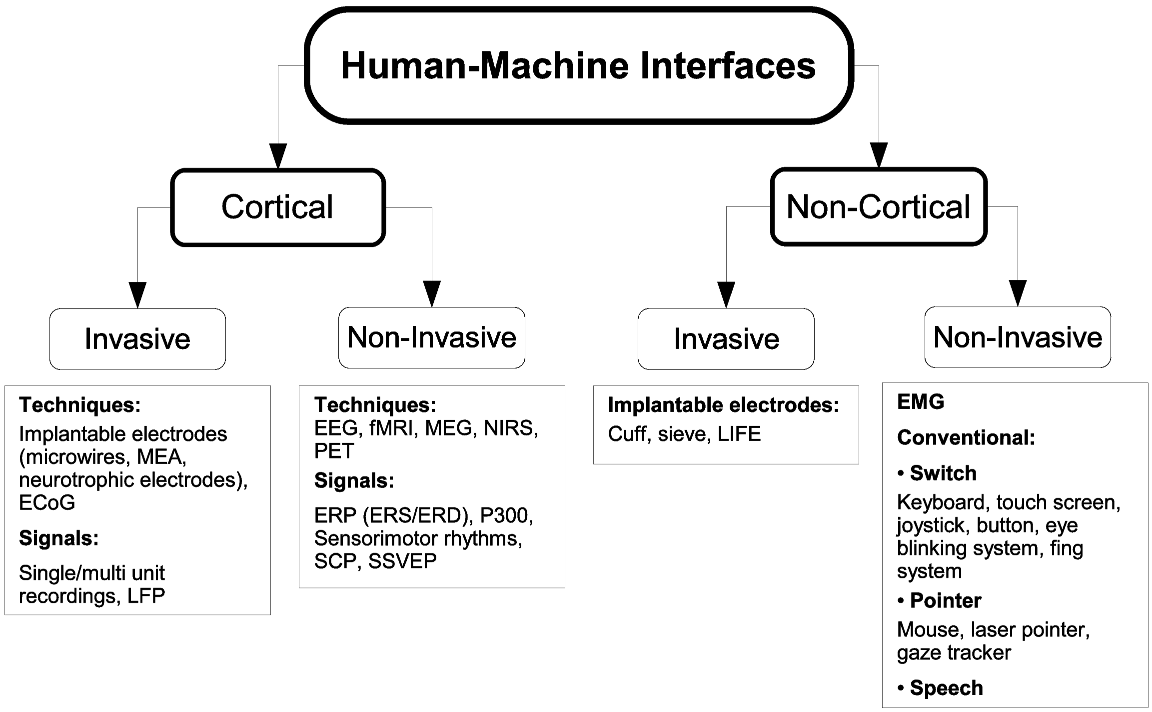

Figure 1: Classification of human-machine interfaces. Examples of signal acquisition techniques and of acquired signals are listed for each class.

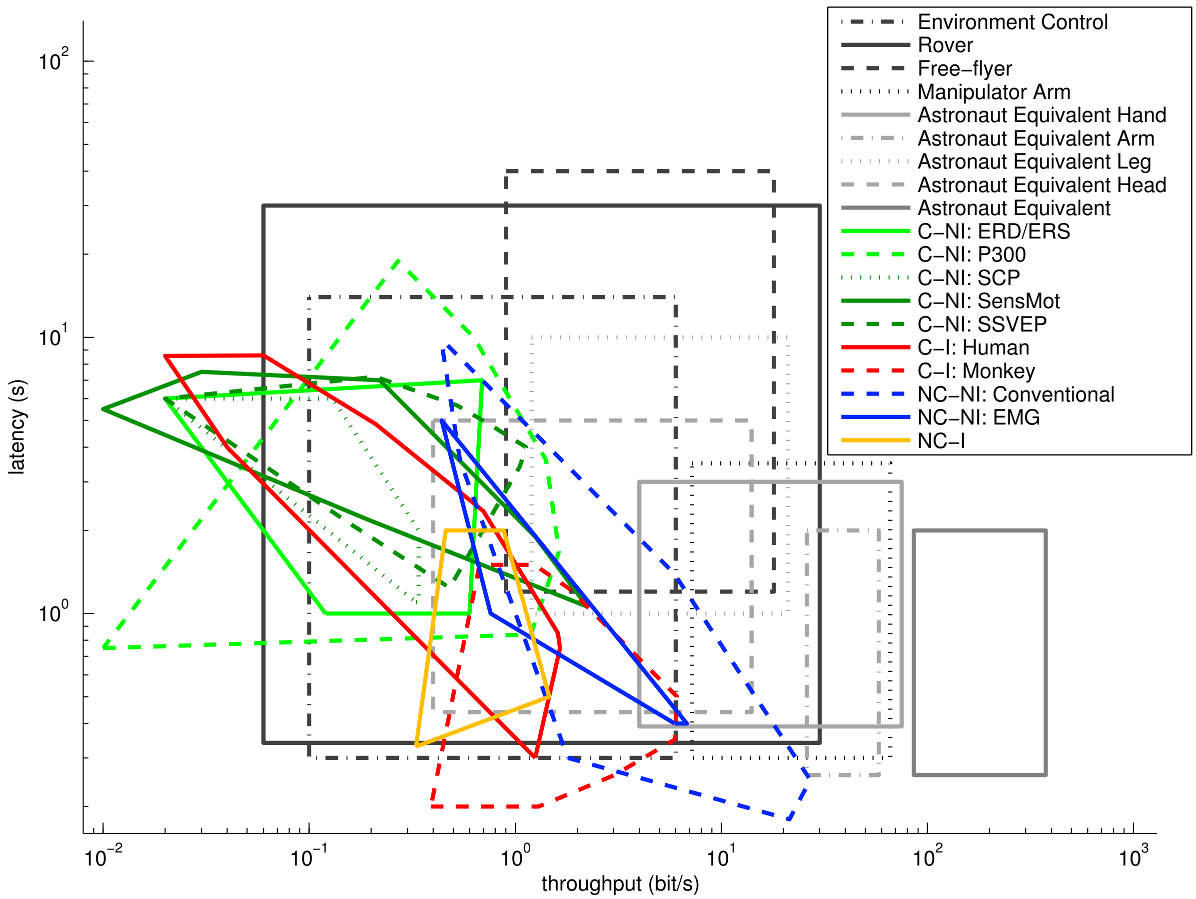

Figure 2: Graphical representation, in terms of latency and throughput, of the requirements of space applications (grey boxes) and of the performance of separate subclasses of human-machine interfaces (areas delimited by coloured convex hulls).

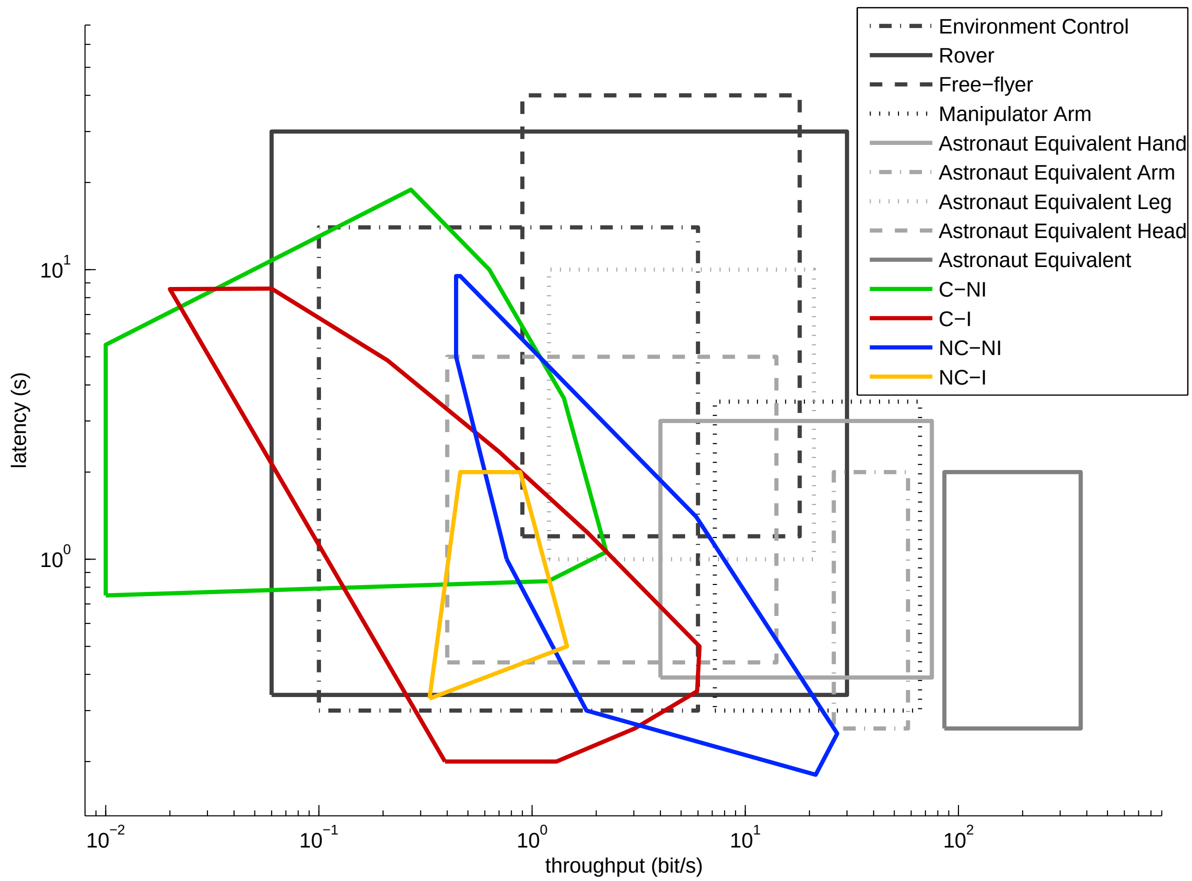

Figure 3: Graphical representation, in terms of latency and throughput, of the requirements of space applications (grey boxes) and of the performance of the four main classes of human-machine interfaces (areas delimited by coloured convex hulls).