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Feasibility of teleoperations with multi-fingered robotic hand for safe extravehicular manipulations

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ABSTRACT

Extra-Vehicular Activity (EVA) plays such a key role that more and more time is devoted to it in space missions. Nevertheless, EVA presents so many intrinsic critical aspects to result highly hazardous for the human operators. This is why a convenient alternative can be offered by telerobotic manipulations, with multi-fingered robotic hands working in teleoperated mode, to safely and remotely replicate the capabilities of the operator's hands. But at present, remotely controlled robotic hands cannot provide the same dexterity of humans, so this work is intended to experimentally evaluate their feasibility and technological limits when operator's hand gestures are one-to-one mapped directly to a robotic hand device. In particular we demonstrated how state-of-the art sensory gloves, used to measure angles of human finger's joints, can introduce averaged errors of 4.6 degrees in angles, and that these errors increase to 6.5 degrees when remotely replicated by standard anthropomorphic robotic hands.

1. Introduction

Extra-Vehicular Activity (EVA) refers to any activity done by an astronaut outside of a spacecraft beyond the Earth's atmosphere. In the late 1960s EVA was necessary to collect lunar material samples and to transfer crew from one spacecraft to another. In 1971, EVA was utilized to retrieve a film and data recording canister. In 1973, EVA was necessary to repair launch damage to Skylab. In 1984, EVA was needful for metalwork of welding, brazing and spraying (Salyut 7 space station). In 1992, EVA was to hand-capture and to repair a satellite (Intelsat VI-F3). In 2001, EVA was required to install the Canadarm2 onto the International Space Station. In 2005, EVA was employed to perform an in-flight repair of the Space Shuttle (mission STS-114). Recently, in 2013, two spacewalks were necessary to install external experiments and prepare the Space Station for a new Russian module.

These examples demonstrate EVA especially applied when dexterous hand manipulations are necessary. However, EVA is potentially very hazardous, and presents many critical aspects. Problems occurred to Alexey Leonov (Voskhod 2 spacecraft), who improperly entered the airlock head-first and got stuck sideways, so he could not get back in without reducing the pressure in his suit, risking "the bends". A defect in the capsule's hatch latching mechanism (Gemini 4) delayed the start of the EVA and put Edward H. White at risk of not getting back to Earth alive. Eugene Cernan, Michael Collins and Richard Gordon (Gemini 9, 10, 11) performed several EVAs, but none was able to successfully work for long periods outside the spacecraft without tiring and overheating. ESA astronaut Luca Parmitano experienced the scariest wardrobe malfunction, for a water leak, in EVA history.

Many challenges are directly related to EVA, such as risks to crew performance, health and safety (such as exposure to harmful solar and other radiations [1]), metabolic demand (oxygen consumption per kilogram per kilometer), and work efficiency. EVA related problems can involve physiological and medical issue [10] as decompression sickness (DCS) (pain, pulmonary problems, memory loss, confusion, headache, extreme fatigue, impaired vision, seizures, vomiting, shortness of breath, unconsciousness, even paralysis), or involve impaired crew performance (as for improperly designed EVA suits [4]).

In spite of those criticisms, EVA continues to be fundamental, given that an enormous increase in EVA hours, from some hundreds of ten years ago to currently planned some thousands in ten years' time [6]. Thus, for the time being, EVA is non-renounceable, but efforts are underway to reduce EVA hours adopting solutions that might provide equal effectiveness. In this direction was the "Rotex" experiment on the NASA Space Shuttle [6], the Flight Telerobotic Servicer (FTS) Project [15], the Mars Surface Reference Mission [7], and so on. Those projects intend to reduce crew extravehicular activity by means of telerobotic capabilities for assembly, maintenance, and inspection applications.

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Our work intends to investigate the possibility for the astronaut to perform dexterity maneuvers remotely controlling an anthropomorphous robotic hand. This is to one-to-one replicate the hand human gestures made inside of the spacecraft, with a robot operator placed outside, with the aim to avoid EVA in a number of circumstances.

2. Telerobotics

In the previous frame, an undergoing solution emerges from the technology of robotic agents operated by telerobotics, combining teleoperation and telepresence [26].

Herein, we underline the aspect related to remote maneuvers of fingered robotic hand devices through hand controllers that, until recently, have been handles, switches, joipads and similar (more or less complicated ensemble as, for instance, the Martin Marietta/Kraft or the RSI Research Hand Controller). These controllers require time consuming training to acquire skillfulness and, moreover, the more complicated tasks to execute, the more Degree Of Freedoms (DOFs) of robotic hands are necessary. But, with these controllers more DOFs corresponds to more manual control difficulties, more mental demanding skill, increased execution time, and further operator experience and training [20]. That is the reason why, with these controllers, no more than just 6-DOFs have been applied.

The technology has lately set out the framework for the realization of multi-fingered robotic hand working in teleoperated mode, as an exact replica of the whole operator's hand capabilities. The multi-fingered robotic hand can have a very large number of DOFs (similar to those of the operator's hand), but quite no training is necessary for the operator to remotely drive it. This is because the operator does not need to interface with any controllers, but operator's gestures are one-to-one mapped directly to the robot hand device. In this way, operators can apply their own experience and instincts, becoming proficient in few minutes without any training.

This possibility arises from the measure of position and movement of the operator's hand while acts simulating an in-situ operation but on a remotely located target. Nevertheless, the crucial point is that the human hand is a masterpiece of mechanical complexity, capable of performing quite complicated grasping actions and fine manipulations, so the accurate measure of the hand has been not a trivial problem to solve.

A first solution came from the Gesture Driver Project, which was a remote driving interface based on visual gesturing. Hand motions were tracked with a color and stereo vision system, and classified into gestures, by means of a simple geometric model. The gestures were then mapped into motion commands transmitted to the robot for execution [9]. The Gesture Driver opened new interesting possibilities, but it was limited by vision occlusion and obstruction problems.

Another approach came from the utilization of a sensory glove, made of sensors embedded in a glove to convert angular displacements of finger's joints into electrical values, useful to drive a multi-fingered robotic hand. The consequence was the possibility for the operator to use the telerobot in the same way that the human body operates. In this view, a donned sensory glove can drive a "Robonaut", i.e. an anthropomorphic robot configured with two arms, two-five-fingered hands, a head and a torso [12].

Here, we focused on the challenging problems of the measure and the reproduction of finger's capabilities. Previous reports discussed the hand mechanism [21], the vision aspect of guided manipulation [18], the data process and software architecture [13], the dexterity, tactile sensibility, strength and fatigue [8]. However, no or scarce effort has been devoted to the comprehension of the feasibility limits, due to the repeatability and reliability problems in measuring multiple joints of operator's fingers and reproducing them by a robotic hand.

The study presented herein intends to fill that gap. To this aim, we designed and realized an ad-hoc state of the art sensory glove and an electronic interface to drive a reference multi-fingered anthropomorphic hand. This was to determine the currently best values of repeatability and reliability, both for the measure of the flex/extension movements of the human fingers, and for the robotic hand when one-to-one maps human gestures.

3. Materials

3.1. Sensory glove and flex sensors

Fundamental factors regarding sensing technology for space applications are low mass, small size and low power. Different sensors have been adopted to measure different parameters such as positions and displacements, forces, fields, radiations, inertial factors, and even volatile compounds (carbon dioxide, oxygen, etc.) [25].

To accurately replicate the hand capabilities, it is necessary a technology suitable to measure them, which complies with the space requirements (mass, size and power), but admitting repeatability errors as low as possible. This is a challenging task since in a "limited" space, in the fullest sense, the whole hand involves 29 DOFs: 23 in the hand joints above the wrist (including flex/extension, abduct/adduction, rotation movements) and 6 in the free motion of the palm (derived from the wrist, forearm, elbow, and shoulder joint motions).

A suitable technology comes from the sensory glove that is a glove quipped with sensors to measure movements of the fingers. The glove can be realized by means of optical devices (fiber optics [31], optical linear encoders [13]), acoustic devices (as in the Power Glove by Mattel), inertial devices (accelerometers [5], gyroscopes [29]), magnetic devices [16], electromagnetic devices (Hall effect, see Humanware Srl, Pisa, Italy), electrical devices (single [22] or array flex sensors [23]), etc. Different sensing principles led to different sensory gloves. The most relevant commercialized products are the 5th Glove (Fifth Dimension Technologies, Irvine, CA), the Power Glove (Mattel, Inc.), the CyberGlove® (Immersion Corporation, San Jose, CA), the HumanGlove™ (Humanware Srl, Pisa, Italy), the P5 Glove (Cyber World, Montreal, QC, Canada), and the Shape Hand (Measurand, New Brunswick, Canada). The most relevant research products are the TUB-Sensor Glove (Technical University of Berlin), the Sigma Glove (Sheffield University), the Washington University Glove and the Accele Glove (Washington University), the Acceleration Sensing Glove (Berkeley University), the WU Glove (University of Wuerzburg, Germany), and the Smart Glove (Nanyang Technological University, Singapore).

For the most part, these sensory gloves offer sufficient repeatability of the measure, but none of them was born to drive a robotic hand in telerobotic applications for space extravehicular activity.

Therefore, we designed and realized a homemade sensory glove. To this aim, our choice was to adopt flex sensors, because of their electrical stability over time with little or no noise factor influence [17], simple construction, lightness and mechanical durability, fundamental in space applications, but not summarized in other sensing devices.

A flex sensor is essentially an analog resistor, made of ink carbon resistive elements printed on top or within a thin flexible plastic substrate, shaped as a stripe. The ink is very brittle, hence flexion results in microgaps within it. Higher flexion causes greater gaps of the ink resulting in a higher resistance, because the greater the angle the greater the gaps.

Among all the commercially available flex sensors, we selected as the more suitable for our applications the 2 inches polyester