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MOBILE ROBOT TELEOPERATION QUALITY TESTING USING THE VIRTUAL REALITY

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Abstract - Complicated systems controlled by humans are extremely prone to errors that may cause critical and emergency situations. There are areas where use of real objects for training is impossible, such as manned spacecraft. Using practical implementation of max-min testing algorithm, a prototype of an anthropomorphic robot's control training system is developed. The results of experiments on the virtual reality were used to create quality-testing methods for professional training. This methodology was designed to train astronauts, pilots, and operators for other sophisticated technology in high-risk areas.

Index Terms - Anthropomorphic Robots, Extravehicular Activity, Robot Control, Testing Strategies, Virtual Reality

I. INTRODUCTION

The robotsinclusion in theperson (operator) professional activity in extreme environments [1] leads us to the problem of training, simulation and correction of the personal control.The "personal control" term means that there is a person included in the control circuit of the dynamic object. The person uses his own biological sensors to solve the control task.

The purpose and the advantages of robots-assistants in this case are fairlyobvious.A person receives more favorable conditions for operating in extreme environment (like spaceflight). It facilitates the exploration of a poorly-studied region, operator may spend less time in hazardous conditions.Nevertheless, thesafety problem's in a joint operation of humans and robots still remains. In a certain sense, the problems go to a higher level of complexity and requires new technological approaches.

Complex mechanisms like robots still cannot be controlled effortlessly and require special handling skills.Most of these skills people can acquire quite fast and easily on dedicated training courses, but some of them can be acquired only with several years of practice. To reduce the time for training and get unbiased results we use max-min testing algorithm and virtual reality simulation.

II. FEATURES OFA TELEOPERATION ANDROBOT CONTROL DURING SPACE MISSION EXTRAVEHICULAR ACTIVITY

Extravehicular activity (EVA) on the lunar surface, necessary for the future the Moon exploration, involves extensive use of robots. EVA is one of the most complex and energy-consuming activities of the astronaut. For EVA on the International Space Station, there were were developed stringent safety regulations, which need to be taken into account during EVA, especially on the lunar surface. The robot functions include carrying cargo and tools, exploring the terrain, creating and updating digital maps, collecting and transmitting navigation data and data on the status of onboard systems through telemetry channels, which are then sent to the Command Centre of the lunar EVA unit. Therobot-assistant functions can also include monitoring operator activity, informing the observer, controlling the efficiency and safety of EVA in general, transporting (medical evacuation) an injured human to the lunar base, including the mode of maintenance of vital functions (primarily cardio-respiratory).
One of the approaches to robot control is teleoperation [2]: anthropomorphic robots can even follow direct movements of the operator. But due to robot's sensors errors and possible delay between operator's and robot's movements, operators still need tobe trained.

III. VIRTUAL REALITY SIMULATION

The virtual reality (VR) group theLomonosov Moscow State University (MSU) Faculty of Mechanics and Mathematics created hardware and software to apply virtual reality technology for testing and modeling of operator control of a mobile robot on the lunar surface (Fig. 1). Realistic simulation experience was achieved using deep feedback that activates a large amount of the person's biological sensors. Primarily, this includes vision.
To achieve realistic visualization, MSU VR Group in cooperation with Total Vision ltd. developed the 2.5K virtual reality head mounted display (HMD). The HMD was tested as a special training modulepart within the CF-18 centrifuge of Gagarin Cosmonaut Training Center.

It was necessary to determine HMD parameters needed for the training purposes;the image resolution, the viewing angle, a time delay in output of the image to the screen, the speed of pixel blanking, and the value of the imagedistortion at the edges all serve as comparative characteristics. To determine this, we have used a simplified human sight model[3].

The input to the visualization system gives information about the currentrobotmathematical model state and its surrounding objects, which allows us to simulate a lunar mission in real time. One of the HMD characteristics is a total covering of the user's visionfield and real environment replacement by a virtual simulation. This consists of using the operator motion tracking system to transfer real person motion to a virtual space.

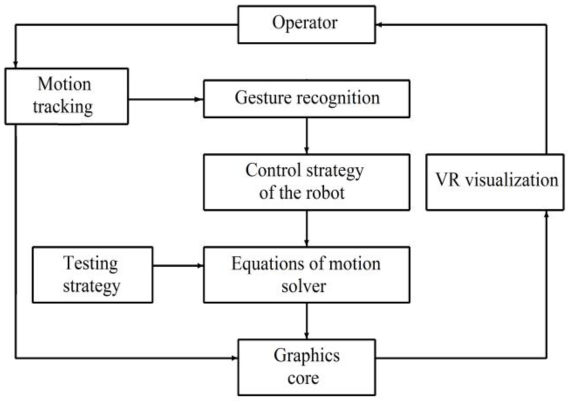

Figure 1. VR-stand structure

That what is called mixed reality. The mixed reality system is a hardware and software suite accomplishing a visualization function of nearby condition for the user with the ability of person's motions tracking and transferring these motions to a virtual space. The technology creates absolutephysical presenceillusion for the person inside the virtual space and allows him to communicate with other people and real objects having a virtual projection.

During the mixed reality complex development, the problem of real and virtual human motions coordination becomes one of the most pertinent. To do that, the new methods development and adaptation of human motion tracking and visualization algorithms are necessary.

Human motion tracking shall be carried out at a frequency of at least 60 Hz. Ultrasonic and radio systems of motion tracking cannot provide the necessary frequency for more than one sensors, and magnetic ones work incorrectly in the presence of a third-party equipment.Thus, we offer the combination of optical and inertial sensors. The existingmotion tracking optical systems have the required frequency, but they are sensitive to overlapping of optical markers – in these moments the data from optical systems are absent or incorrect. Inertial systems aren't subject to overlapping, however they have low accuracy when tracing the linear relocation with the errors accumulated over time.

The development of a hybrid tracking system as a combination of optical and inertial data allows us to achieve the solution without specified issues.

IV. ROBOT PARAMETERS IDENTIFICATION

Let us assume that the mechanical part of the movable and immovable partsrobot consists: cores of fixed and variable length, and various types rotating joints.

The sensors in the mechanisms of the robot may be not precise enough or absent altogether, and the robot geometric parameters change with time because of deformations due to constant loads. These factors negatively affect the robot's control and accuracy of the virtual simulation.

Hight-quality simulation required construction of the operator and robot motionmathematical model and a model parameter identificationmethod based on external measurements.This study includes researches in the field of mechanics and math, in particular optimization of algorithms of a global extremum search. It is also necessary to define the minimum quantity of the sensors needed for the correct motion tracking. It should be noted that the improvement of operator's continuous three-dimensional model binding to the virtual bones are necessary to avoid visual distortions during the activity of the operator.

Identification of robot parameters and robot positioning can be constructed without using measurements from internal sensors located in the robot mechanisms. The authors developed an algorithm of semi-automatic identification a robot model parameters with a system of opticalmotion tracking.

Suppose that there are certain robot's geometrical parameters measurements (e.g. with a ruler) as initial approximations. A set ofoptical motion tracking system light-reflecting markers is placed on the robot [4], providing visibility of the markers tothe system cameras from any possible robot position.

From the motion capture system measurements fixed coordinate system Oxyz is obtained. This system is fixed in the room where the robot is located. Optical motion tracking system readings also show coordinates of markers of Oxyz frame at each moment of time. There is no loss of generality in supposing that the immovable base of the robot is located relative to the Oxyz reference frame in the same way as in the model case.

The optical motion tracking system is used to carry out the experiment, as a result of which it is required to obtain the coordinates of the markersP_i^u in a fixed reference frame for some control values $u(\cdot) \in U$, where i is the corresponding marker number. Since the robot takes some time to get to the new position, and there is random noise in the optical motion tracking system, we will consider P_i^uas the averaged readings at some time interval after the robot stops.

Before the experiment, a uniform lattice is constructed in the control space U. To increase the speed of the experiment, instead of an arbitrary path along this lattice, the Hamiltonian path is used, and motion is recorded along the nodes of this path.

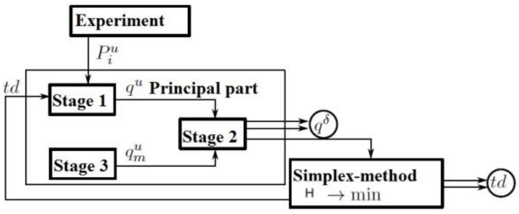

Figure 2. Identification algorithm

The main part of the algorithm consists of three steps(Fig. 2):

1. Search for the reference frame related to the end effector of the real robot and it's rotationq_u with respect to the immovable (fixed) system,
2. Calculate relations of the orientation q_u^m of the model robot and its control u,
3. Search of mutual orientation of model and real reference framesq^δ.

The output of the main part of the algorithm gives us the error functional H.

$$H = \sum_u ||(q^u \circ q^\delta \circ (q_m^u)^{-1} - q^e)||,$$

Whereq^e is a quaternion with a unit scalar part and a zero vector part [5].
H is minimized on the space of geometric parameters tdof the robot using the Nelder-Mead simplex method [6].
This method gives us a good approximation of the robot parameters with up to 5 times higher accuracy than with direct optical motion tracking system measurements.

V. TESTING STRATEGY

To achieveappropriate training results, we simulate not only normal, but also abnormal, and emergency operating conditions. Simulated perturbations are modelled using differential game theory.

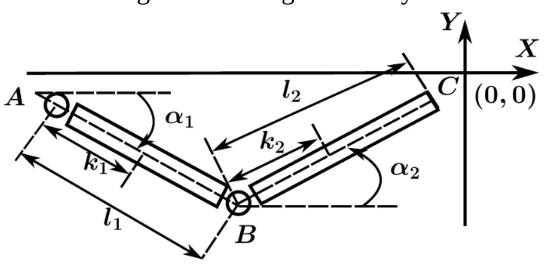

Figure 3. Manipulator

So, let's consider the problem of testing the astronaut's personal robot control when he is trying to move a cargo from one point to another. In the sample case, the manipulator is modeled by a two-link chain (Fig. 3): AB – shoulder (first link), BC - forearm (second link). They are connected by a cylindrical joint. Movement occurs in a vertical plane, the shoulder joint A is fixed. Masses $-m_1, m_2$, central inertia moments – I_1, I_2, u_1, u_2 - force moments, which develop in the corresponding joints. These force moments are bounded.

k_1, k_2 are coefficients, that set a relative position for a center of mass on its longitudinal axis. They are defined by equations:

$$k_i = \frac{p_i}{l_i},$$

where p_i- distance from i^{th} joint longitudinal axis to the center of mass, i=1,2.
Lagrange's equations of motion:

$$\ddot{p} = A^T\left(\frac{1}{2}\dot{p}^T\frac{\partial A}{\partial p}\dot{p} - \frac{\partial V}{\partial p} - \dot{A}\dot{p}\right) + A^{-1}Q,$$

$$A = \begin{pmatrix} I_1 + m_1 l_1^2 k_1^2 + m_2 l_1^2 & 2m_2 l_1 l_2 k_2 \\ 2m_2 l_1 l_2 k_2 & I_2 + m_2 l_2^2 k_2^2 \cos(\alpha_2 - \alpha_1) \end{pmatrix},$$

$$V = m_1 g l_1 k_1 \sin\alpha_1 + m_2 g(l_1 \sin\alpha_1 + l_2 k_2 \sin\alpha_2).$$

The carried mass is added to point C: $m_2 = \widetilde{m_2} + \Delta m_2$, $k_2 = \widetilde{k_2} + \Delta k_2$.
Controls: $Q(\cdot) = u(\cdot) \in U$,
perturbations:$\omega(\cdot) = (\Delta m_2 \quad \Delta k_2)^T \equiv const \in W$.
Time is determined: $t \in [t_0, t_k]$.

Initial conditions: $p(t_0) = (\dot\alpha_1^0 \quad \dot\alpha_2^0)$, $(x, y)(t_0) = (x_0, y_0)$.

Quality control functional: $J = ||(x, y, \dot x, \dot y)(t_k)||^2$.

We consider the two-person zero-sum dynamic game Γ = (W,U,J) of two influences on system, the perturbation ω and the control u, which are assumed to be independent.
Control strategy shouldtry to lead cargo to the ending point (0,0) even with the worst perturbations:

$$J^0 = J(\omega_0, u_0) = \min_{u(\cdot)\in U}\max_{\omega(\cdot)\in W} J$$

Perturbations strategy does the opposite thing:

$$J_0 = J(\omega^0, u^0) = \max_{\omega(\cdot)\in W}\min_{u(\cdot)\in U} J$$

Just as in the case of any two-person zero-sum game, we have the obviousinequality:

$$\max_{\omega(\cdot)\in W}\min_{u(\cdot)\in U} J \le \min_{u(\cdot)\in U}\max_{\omega(\cdot)\in W} J$$

The maximin testing technique [7] permits us to obtain objective performance indices for the accuracy of the control under extreme conditions.
The following three stages can be singled out in the maximin testing problem:
1. At the first, preliminary stage, we find the least (best) estimate of the control performance indexJ_0 (excellent result) and the worst strategy for perturbations ω^0, with the use of a computer solution of the maximin problem:

$$J_0 = J(\omega^0, u^0) = \max_{\omega(\cdot)\in W}\min_{u(\cdot)\in U} J \le J(\omega^0, u) \ \ \forall u$$

2. At the second, main stage, we carry out the testing process in the form of virtual simulation with the use of the optimal perturbation strategy found at the first

stage. A real estimate of the control performance is found as a result of simulation: $\tilde{J} = J(\omega^0, \tilde{u})$;

3. At the third, concluding stage, we compare the best and real estimates, give a rank on a 100 point scale: $\frac{J_0}{\tilde{J}} \cdot 100$,and issue recommendations for further training.

VI. THE RESULTS

A. Matrix game with piecewise constant control

The calculated results of J^0 and J_0(in meters) for some discrete approximation variants of U (for $J^0 = \min_{u(\cdot)\in U} \max_{\omega(\cdot)\in W} J = J_0$ there is just one value).

t\upartition	2	3	4	5	6
1	0.61	0.61	0.24 0.19	0.52 0.25	0.12
2	0.52 0.27	0.44 0.17	0.24 0.15	0.14 0.05	0.05 0.02
3	0.27 0.15	0.16 0.09	0.13 0.1	0.03 0.02	
4	0.36 0.15	0.11 0.03	0.03 0.01		
5	0.11 0.08	0.04 0.003			

Manipulators parameters values:

$$I_1 = 0.07239\ \mathrm{kg}\cdot\mathrm{m}^2, \quad m_1 = 2.413\ \mathrm{kg},$$
$$I_2 = 0.0239\ \mathrm{kg}\cdot\mathrm{m}^2, \quad m_2 = 1.146\ \mathrm{kg},$$
$$k_1 = 0.5, \quad l_1 = 0.6\ \mathrm{m},$$
$$k_2 = 0.5, \quad l_2 = 0.5\ \mathrm{m}.$$

Time $\in [0,2]$ s, $M = 2$ kg , $g = 0\ \mathrm{m/s^2}$, $|\Delta M| \le 0.9$ kg , $|\Delta k| \le 0.2$. Let us $u(\cdot) \in KC$ such that $|u_1| < 35\mathrm{kg}\cdot\mathrm{m}^2$.

B. Matrix game with feedback control

$u(x) = K(x - x(T_1))$, where $x(T_1)$ is the final configuration, $K \in U$, $K(1) \in [-180,\ 0], K(2) \in [-120,\ 0], K(3) \in [-140,\ 0], K(4) \in [-55,\ 0]$. We obtain the following resultsof J^0 and J_0 (in meters) for different partitions with respect to t and K:

t\Kpar-tition	2	3	4	5
1	0.0031	$1.27\cdot10^{-4}$ $9.8\cdot10^{-5}$	$1.5\cdot10^{-4}$ $6.6\cdot10^{-5}$	$1.14\cdot10^{-4}$ $4.5\cdot10^{-5}$
2	0.0029	$3.7\cdot10^{-4}$ $1.07\cdot10^{-4}$	$3.13\cdot10^{-4}$ $1.7\cdot10^{-4}$	
3	$6.74\cdot10^{-4}$	$1.6\cdot10^{-4}$		
4	$6.67\cdot10^{-4}$			

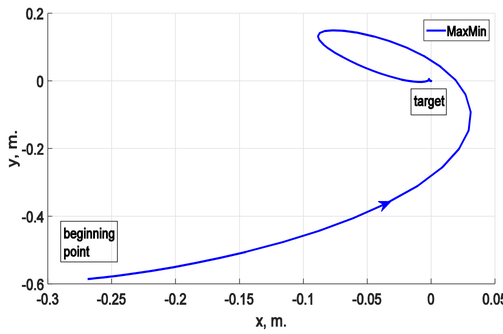

Figure 4. Example of the manipulator's end effector trajectory

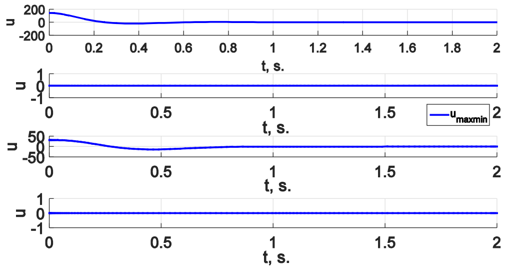

Figure 5. Example of the manipulator's control

Virtual simulation

We used Total Vision virtual reality headset as visualization system and HTC Vive Lighhouses [8] for motion tracking. Experiment involved 5 operators.

The control of the virtual manipulator was built in the form of feedback. The feedback coefficients: $K = (-180, -120, -140, -55)$, $\omega = (-0.9, -0.2)$.

Following results were obtained:

Parameters / Subjects	№1	№2	№3	№4	№5
Movements quantity	18	99	36	71	16
Overshoots quantity	0	0	0	2	0
Expectation of J (m)	0.02	0.07	0.08	0.04	0.02
Expectation of rank	19	13.9	16.6	23.7	25.9
Median of J (m)	0.02	0.03	0.03	0.03	0.02
Median of rank	14	12	10	11	19

Overshoots are the cases such that the rank is more than 100 points. The real controls are more complicated than the class of functions which approximate the controls.

Average rank increases during the experiment progress (Fig. 6). In the end, the average rank becomes lower, most likely because of operator tiredness. Emissions are present only for one subject and are less than 3% of the total number of motions.

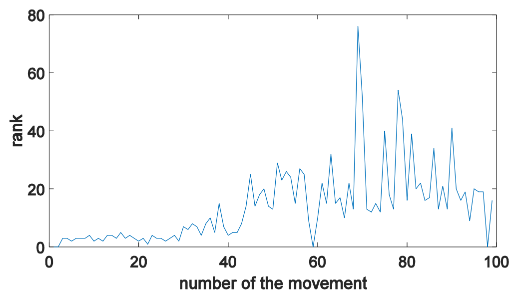

Figure 6. Ranking

CONCLUSION

Max-min testing method was developed several years ago, but only now we have enough computational powers to use it in real training systems.

Described testing and virtual simulation method could be used not only for robot control training, but for other operation tasks. We can also use this testing methodology for certification purposes.

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