Manipulator Control for Physical Astronaut-Robot Interaction

Melak Zebenay*, Seppo Heikkilä **

*Germany Aerospace Center, DLR, Germany
e-mail: Melak.Zebenay@dlr.de

**Automation Technology Laboratory, Aalto University, Finland
e-mail: Seppo.Heikkila@tkk.fi

Abstract

The future of astronaut-robot cooperation applications is highly dependent on the capability to perform safe and efficient physical interaction using the robot's manipulators. *WorkPartner*, Aalto University's mobile service robot, did not have any control algorithm that would enable safe human-robot physical interaction applications. This paper addresses this problems by developing compliance control capabilities for the *WorkPartner* manipulators. The developed compliance control is based on an admittance control algorithm that is modified to incorporate different operation modes. The control algorithm is implemented on the *WorkPartner* simulator as well as on the real *WorkPartner* robot manipulators. The selected modes of operation are ”follow movement”, ”hold position”, and ”adapt movement”. The test results show that the implemented control algorithm is capable of providing all the three examined manipulator behavior modes.

1 Introduction

Astronaut-robot cooperation could simplify exploration and enable large-scale constructions in the Moon and Mars. The astronaut-robot cooperation is seen to have profound advantages such as; human crews can be lesser in number; astronauts will be able to do more physically demanding tasks with the help of robots; there will be less costs to send robots rather than astronauts, and the risks will be minimized because robots are less sensitive to radiation than humans.

Aalto University's *WorkPartner* [1] is a service robot that has rich features such as multi-modal user interfaces and a hybrid wheel-walking locomotion system which are all desired features for a planetary astronaut assistant robot. Figure 1 shows the two manipulators of the *WorkPartner* as well as its upper body which it mainly uses to interact with humans.

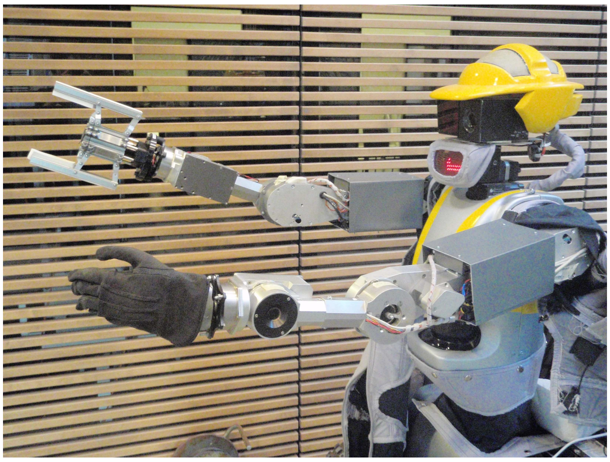

Figure 1. *WorkPartner* robot with its two manipulators.

The objective of this research is to develop the capabilities of the *WorkPartner* robot, also referred to as SpacePartner, to perform safe and efficient physical interaction using its manipulators. The idea is to enable the astronaut to be able to change the robot's manipulator behaviors seamlessly and intuitively according to performed task.

In this paper the *WorkPartner*'s manipulators are used to test the developed manipulator control algorithms and to verify that the desired behaviours can be achieved. The starting situation is, however, quite challenging because the original *WorkPartner* manipulator control system has only very limited support for Physical Human-Robot Interaction (PHRI) applications. This is mainly because the manipulators' motor controllers have only support for position control mode that can not be easily modified or extended to provide compliant behaviours.

2 Manipulator Control for PHRI

The control of robotic systems in physical interaction with human has been a subject of research for many years. Some thorough introductions to existing PHRI control methods can be found from [2, 3, 4, 5], pointing out fundamental requirements for force/torque control such as importance of sufficient control bandwidth. Requirement assessments for a robotic astronaut assistant, identifying the most likely operational domains and desired cooperation system components, have been presented, for example, in [6] and [7].

This paper focuses, however, on the robot manipulators control when performing tasks in cooperation with humans, and especially with astronauts that work on the future planetary Mars and Moon missions. For example, the papers [8] and [9] present different methods for facilitating the safe interaction between robots and humans in unknown environments. The most commonly used algorithms for implementing the compliance control are stiffness control, impedance control and hybrid position/force control. These algorithms can be implemented using the outputs from force/torque and position sensors.

The robot's manipulator control approach has to be selected based on the used robot configuration and its expected interaction applications. For example, *WorkPartner* had only position sensors at the joints, without any joint force/torque sensors, and there was not practically enough free space to add any external joint force/torque sensors. This indicated that the only feasible options were to mount either an end-effector force/torque sensor or to replace the old motor controllers with new new ones.

The manipulator control strategies for PHRI are usually based on the use of the following control algorithms or a combination of them: stiffness control [10], impedance control [11], and direct force control. Most of the existing approaches use compliance control algorithms, or flexible robot manipulators, to enable safe and efficient interaction. This paper presents a control approach for safe and efficient interaction which combines admittance control and the user's behaviour request inputs in order to enable seamless changes in the manipulators' modes of operation.

2.1 *WorkPartner* robot and SimPartner

WorkPartner is a centaur-type service robot which was originally designed to assist humans in light outdoor tasks, but is currently used for to study astronaut-robot interaction. The robot upper body torso has two Degrees of Freedom (DOF), for tilting and rotating the whole upper body, and the torso has further two five DOF manipulators attached to it. When used with its mobile platform, the manipulators can reach any positions and orientation in three dimensional space, which results in advanced flexibility in comparison to standard industrial robots.

All the manipulator joints have an encoder and potentiometer to provide position feedback for control. The joints are controlled by a Proportional Integral Derivate (PID) controller. The original motor controllers were not accessible for modifications and integration with the main control system. Due to this limited flexibility of the controllers and insufficient performance, the motor controllers were changed into commercial Elmo Whistle 5/60 motor controller. These Elmo motor controllers enable to control the manipulators either using position, force/torque or speed requests.

SimPartner is a dynamic rigid-body robot simulator which has been developed based on open source projects such as Open Dynamic Engine (ODE) [12]. A screenshot from the SimPartner with the used WorkPartner model can be seen in Figure 2. For this paper, the SimPartner simulator is further developed to suit the requirements of the examined control algorithm tests. The following modifications are made to the SimPartner simulator in order to support the testing requirements:

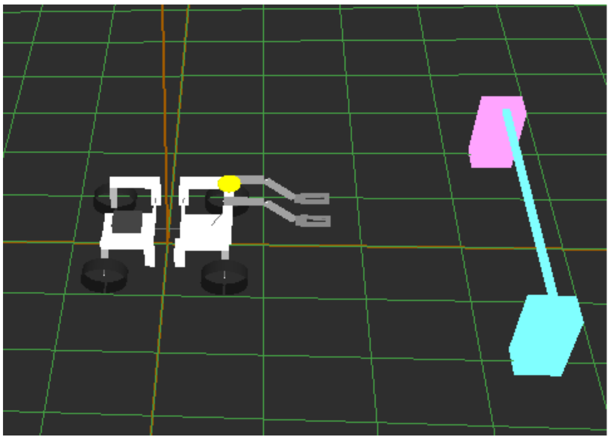

Figure 2. A screenshot of the SimPartner simulator with the *WorkPartner* robot model.

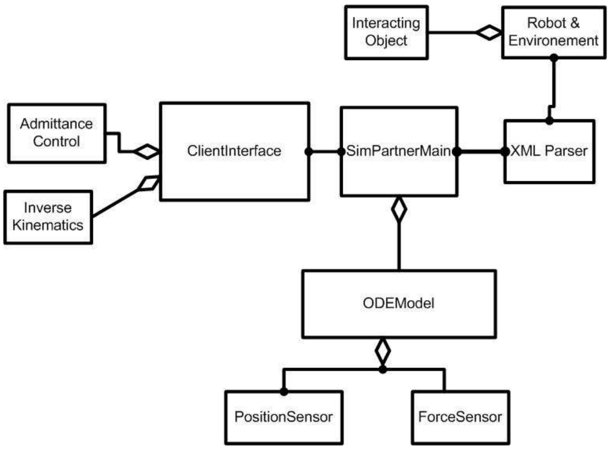

Figure 3. A class diagram of the modified SimPartner simulator.

- Force sensors on the shoulder, elbow and wrist joints.
- Position sensors on the shoulder, elbow and wrist joints.
- The robot model is simplified to increase the processing speed.
- Interacting object are added to the environment to apply forces to the manipulators.

Figure 3 shows a simplified class diagram of the modified SimPartner simulator.

2.2 Compliance control algorithm for *WorkPartner*

In this paper position-based impedance control called admittance control, together with an operation mode selector, is implemented. The position control is implemented using of the commercial Elmo Whistle 5/60 motor controllers. Figure 4 shows the proposed control algorithm scheme.

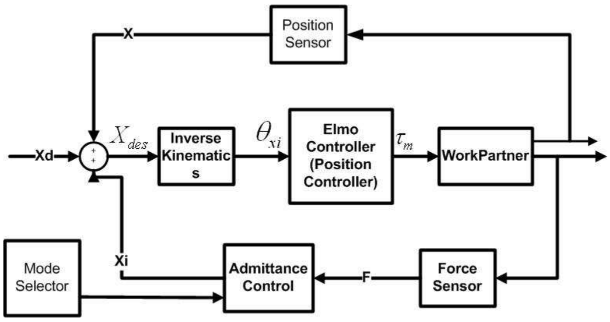

Figure 4. Proposed control algorithm based on admittance control with added behavior selection switch.

The position-based impedance control algorithm allows the robot to interact both in constrained and unconstrained areas. The steps followed to implement the control algorithm are as follows:

- The external force, F, is measured using a force sensor. The force is measured using a sensor mounted at the manipulator endpoint and reported to the control unit.
- The impedance (admittance) control algorithm determines the next end-effector linear positions, as shown in Equation 1, from the measured force vector and based on the selected mode of operation. The mode of operation determines the possible range of values of the stiffness constant. For example, ”follow movement” expects a low value of stiffness gain so that the robot will follow the direction of force applied to it.

  $$\chi_{des}(s) = \chi(s) + \chi_d(s) - \frac{\Delta f(s)}{K} \qquad (1)$$

  where $\chi(s)$ is the relative position of the end-effector, $\chi_d(s)$ is the desired position of the end-effector, and K is the stiffness constant.
- Using the inverse kinematics, the linear position from the previous step, the desired position and the position output from the admittance control, the algorithm calculates the angular positions of each joints according to Equation 2.

  $$q_d = K^{-1}(\chi_{des}) \qquad (2)$$
- The Elmo motor controller uses the calculated angular positions to generate a corresponding torque command for each of the robot joints.

The admittance based control algorithm is implemented on the *WorkPartner* simulator as well as on the real *WorkPartner* manipulators, based on the above presented steps, in order to enable the three selected manipulator behavior modes. These three selected modes are ”follow movement”, ”hold position”, and ”adapt movement”. Their definition from the control algorithm point of view is shown in Figure 5. These behaviour modes were implemented on the *WorkPartner* robot by estimating the end-effector forces using the active currents of the Elmo motor controllers.

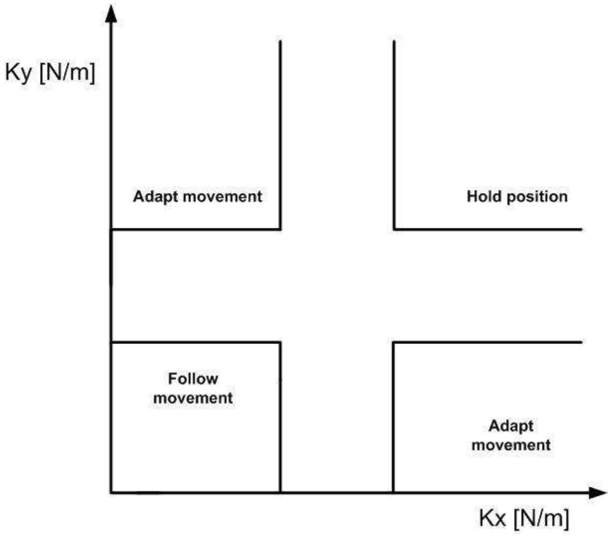

Figure 5. Operation modes of the implemented compliance control algorithm.

3 Results and Analysis

The developed control algorithm is tested using SimPartner simulator and with the *WorkPartner* manipulator. Two Elmo controllers are mounted on two joints of one of the manipulators to test the control algorithm. These controllers are used to estimate the force at the end-effector from the active current and also to control the joint angles.

3.1 Follow movements

The follow movement demonstration case describes the possibility of the human to lead the robot arm to a target location by applying external force/torque to the manipulator. This demonstration is implemented on SimPartner using admittance control without a damping constant which is the stiffness control algorithm because the speed of the end-effector is not used.

In a ”follow movement” case, the user can choose from the stiffness constant values K_X and K_y approximately in the range shown in Figure 5. These linear position values will be converted to corresponding joint angles using inverse kinematics.

Figure 6 shows the position change errors, which generate the joint torque commands to follow the applied force, using different stiffness values. Both in X- and Y-direction the allowed position errors are higher with smaller K values and smaller with higher K values. The low K values can be thus directly used to allow the robot manipulator to follow movement according to external force. The results from the graphs are not ideal due to variation of interaction forces on both the X-axis and Y-axis.

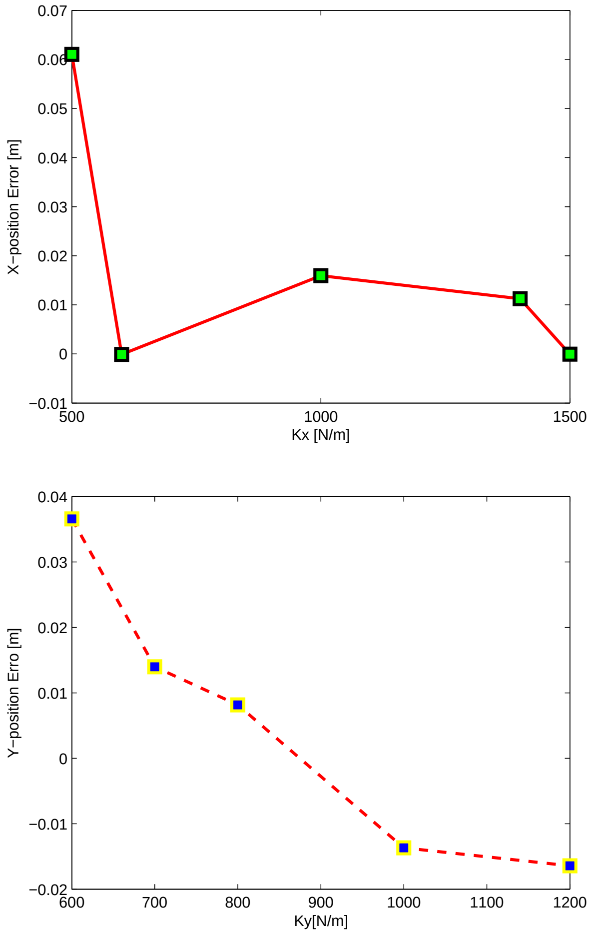

Figure 6. X-position (above) and Y-position (below) changes due to external force on the end-effector.

3.2 Adapt movement

The ”adapt movement” demonstration case illustrates the possibility of the human to lead the robot arm to a target location in one direction, or to the direction of the applied force, while keeping the arm location constant in the other possible directions. This demonstration is also implemented on the SimPartner using admittance control without a damping constant which is the stiffness control algorithm.

Like the ”follow movement” case, this demonstration is developed in such away that the user is allowed to choose the ”adapt movement” mode of operation from computer keyboard. After that the user can choose an appropriate stiffness constant. For example if the user wishes to adapt the movement in the x-direction of the force frame by keeping the y-direction constant, the application expects a high value for K_y and a small value in K_x . This expected behaviour can be seen in Figure 6. The position error can be seen decreasing as the values of the stiffness increases. In this way the value of stiffness can be directly used to constraint the allowed direction of movement.

3.3 Hold position

The ”hold position” demonstration case also describes one mode of operation that enables the human to keep the manipulator in a desired position. The algorithm for this demonstration case is implemented on the SimPartner simulator. Similarly, the user is allowed to choose the mode of operation and then give stiffness values in the approximated range as shown in Figure 5 which are large values of K_X and K_y. These high values of stiffness are converted to very small values of linear position which will hardly change the current position. The higher the value of the stiffness, the more accurately the end-effector holds the previous position. Figure 7 shows the position error using different values of stiffness K_x and K_y which have a small error when the stiffness value is higher.

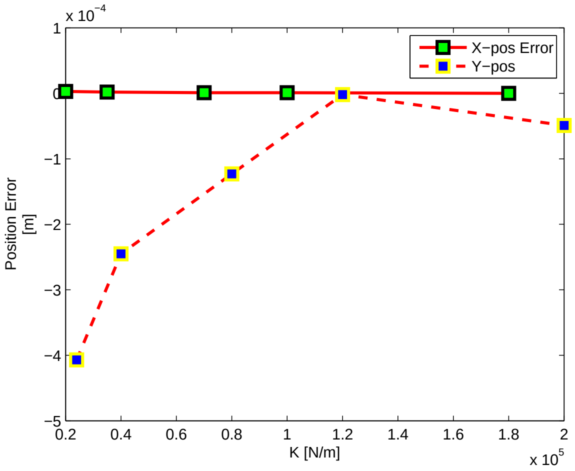

Figure 7. X- and Y -Position changes, from initial position to final position due to external force, with high values of stiffness Kx, Ky.

3.4 Compliance control implementation on *WorkPartner*

The above simulation results demonstrate that the suggested control algorithm is working as expected in the simulated environment. Thus next, the compliance control algorithm is implemented and tested with the real *WorkPartner* manipulator to verify the above results in practice. For this, two Elmo motor controllers are used at the elbow and shoulder joints of the manipulator.

The Figure 8 shows the effect of the stiffness change with respect to the position error at the shoulder joint when a 3.11kg object is put at the end-effector of the manipulator to apply force directional to gravitational force. When the value of the stiffness is increased, the stiffness of the manipulator increases which changes the state from follow movement to hold position. When the stiffness is changed from 100 to 40000, the manipulator is changed from follow movement to approximately to hold position mode. This test result demonstrates the correct behavior of two modes of operation, i.e. follow movement and hold position. The third adapt movement mode is a combination of this two modes at two different axes.

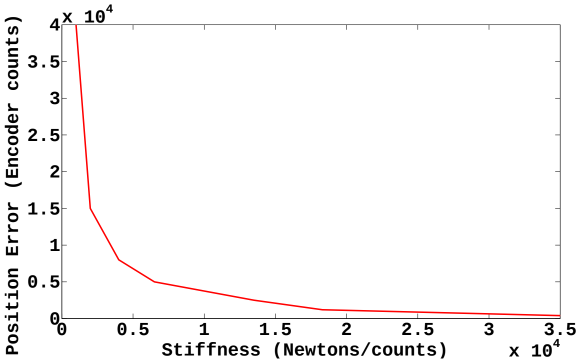

Figure 8. Stiffness values versus position error for the real *WorkPartner* robot's manipulator joint.

4 Conclusion and Future Work

This paper examined how to enable physical astronaut robot interaction capabilities for the *WorkPartner* service robot by implementing a manipulator control algorithm which enables changing the behaviors of the robot manipulators in a seamless manner. In the implemented manipulator control application, the manipulator's behavior was changed using only one stiffness value of the control algorithm. The continuous range of possible control values enables a seamless and intuitive way for the astronaut to change between different manipulator control behaviours.

It was shown, for example, that the *WorkPartner* robot can follow in the direction of the interacting force until hold is requested by the human. This behavior was implemented on the *WorkPartner* robot using the end-effector interaction force, determined from the motor controllers' currents, and by changing the control algorithm's stiffness values based on the selected behaviour mode. The test results on the simulator and on the real *WorkPartner* showed finally the select behaviours to perform as expected.

4.1 Future work

The presented manipulator control algorithm is not however alone enough to realise the envisioned goal of efficient and safe astronaut-robot physical interaction. In addition to further developing the manipulator control algorithms, there is several other issues to be studied. For example, one important issue is to further develop the astronaut assistant robot's capabilities to recognise and understand the cooperating human's actions. This could in the ideal case enable the robot to mitigate in advance all the unexpected or dangerous movements. This could be done, for instance, using both automatic activity recognition algorithms and by developing more usable and error tolerant task communication interfaces.

References

[1] A. Halme, I. Leppänen, J. Suomela, S. Ylönen, and I. Kettunen, "WorkPartner: interactive human-like service robot for outdoor applications," The International Journal of Robotics Research, vol. 22, no. 7-8, p. 627, 2003.

[2] J. Carufel, E. Martin and J.-C.Piedboeuf, "Control strategies for hardware-in-the-loop simulation of flexible space robots", IEEE Proceedings of Control Theory and Applications, vol. 147, No. 6, pp. 569-579, November 2000.

[3] M. Vukobratovic and A. Tuneski: 'Contact control concepts in manipulation robotics - an overview', IEEE Transactions on industrial electronics, vol. 41, pp. 12-24, 1994.

[4] R. Ikeura and H. Inooka "Variable Impedance Control of a Robot for Cooperation with a Human" IEEE International conference on Robotics and Automation, 1995.

[5] S.D. Epptnger and W.P. Seering: 'Understanding bandwidth limitations in robot force control'. Proceedings of IEEE international conference on Robotics and automation, Raleigh, North Carolina, pp. 904-909, 1987.

[6] S. Heikkilä, F. Didot and A. Halme, "Centaur-type Service Robot Technology Assessment for Astronaut Assistant Development," in Proceeding of Advanced Space Technologies for Robotics and Automation (ASTRA), 2008.

[7] N.A. Cabrol, H. Bualat, M.G. Sierhuis, M. Grin, E.A. Kosmo, J.J. Trevino, R.C. Eppler, D. Baker, and K. Huber "Results of the first Astronaut-Rover (ASRO) field experiment - Lessons and directions for the human exploration of Mars", The Fifth International Conference on Mars, Pasadena, US, July 1999.

[8] A. Albu-Schaffer, O. Eibergerand, and G. Hirzinger "Soft Robotics", IEEE Robotics and Automation Magazine, 2008.

[9] A. Santis, V. Lippiello, B. Siciliano and L. Villani "Human-Robot Interaction Control Using Force and Vision", Advances in Control Theory and Applications, Springer, pp. 51-70, 2007.

[10] J. K. Salisbury, "Active stiffness control of a manipulator in Cartesian coordinates", in Proc.19th IEEE Conf. Decision and Control, Albuquerque, US, pp. 95-100, 1980.

[11] N. Hogan, "Impedance control: An approach to manipulation", Parts I-III, ASME Journal of Dynamic Systems, Measurement and Control, vol. 107, pp. 1-24, 1985.

[12] P. Heiskanen, S. Heikkilä, A. Halme, "Development of a dynamic mobile robot simulator for astronaut assistance", Proceedings of 10th ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA), Noordwijk, Netherlands, November, 2008.