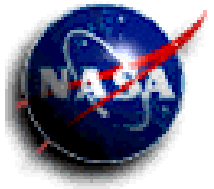


Space Robotics

Brian Wilcox - JPL

Pending Review (Paul Schenker - JPL

Rob Ambrose - JSC)

20 July 2004

Robots for use in Space

General-purpose devices where the precise function or mission sequence is not specified at the time of design that can:

- explore,
- assemble, maintain, and repair space hardware, and
- assist humans in space.

Major Laboratories and Investigators (I)

Jet Propulsion Laboratory
Planetary Exploration Focus

- Planetary rovers (MER, Sojourner, MSL) for reaching and sampling sites of scientific interest
- Subsurface Explorers to get pristine or otherwise unreachable samples.
- Aerobots (atmospheric robots) for Mars, Venus, Titan

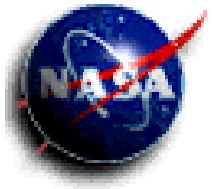
Johnson Space Center
Astronaut Assistant Focus

- Robonaut (a dexterous human-form robot that can use tools and fixtures designed for suited astronauts)
- Aercam (a free-flying spherical "flying eyeball" for EVA inspection)

Major Laboratories and Investigators (II)

- Ames Research Lab plays a major role in researching advanced software techniques using K9 rover and PSA free-flying intra-vehicular inspection robot as key development platforms.
- Goddard Space Center is developing capability for robotic repair/upgrade of Hubble Space Telescope.
- Langley Research Center has significant expertise in robotic assembly of space structures.
- Carnegie Mellon University has had substantial funding over many years to develop advanced space robots.
- University of Maryland, Stanford, MIT and other Universities have or had substantial NASA funding.

Major Laboratories and Investigators (III)



- Lockheed Martin (then Martin-Marietta) had a ~$400M project in the 1980's to build the Flight Telerobotic Servicer
- The Canadian government "donated" the Shuttle Remote Manipulator System, Station Remote Manipulator System, and the Special-Purpose Dexterous Manipulator.
- Boeing started an effort in space robotics in the 1980's and acquired MacDonnell-Douglas (who had a significant effort going at the time). Boeing is the integrating contractor for the Army Future Combat Systems, coordinating efforts of major robotics contractors such as General Dynamics.

Major Theoretical Accomplishments and Practical Embodiments (I)

- JPL's Sojourner and MER Mars Rovers demonstrate practical work on Mars despite once-per-day commanding using 3-D waypoint and activity-site designation in frozen stereo images, real-time range mapping, hazard detection and avoidance, visual odometry, and instrument arm compliance control.
- JSC's Aercam and Robonaut demonstrate practical inspection and teleoperation in space or space-like settings with small closed-loop time delay. Practical autonomy for operation with several-second time delay (Earth operators) is being developed and demonstrated with no apparent show-stoppers.

Major Theoretical Accomplishments and Practical Embodiments (II)

- Canadian Shuttle and Station RMS arms have performed valuable service but are difficult to control (two 3-dof hand controllers, no force control, no predictive dynamics control)
- University of Maryland "Ranger" flight experiment incorporated many advanced features but was not flown. Neutral buoyancy experiments were also seminal.
- JSC "Charlotte" robot flight experiment demonstrated 6-DOF control using only wires in tension.

Most Influential Papers (I)

- T. Sheridan, "Space teleoperation through time delay: review and prognosis," IEEE Trans. Robotics & Autom., Vol. 9, No. 5, pp. 592-October, 1993.
- B. Wilcox, "An Evolutionary Strategy for Telerobotic Operation via Geosynchronous Relay", IEEE International Conference on Robotics and Automation, Workshop on Space Robotics, Scottsdale AZ, May 1989.
- Tutorial on Robotics (Eds., C.S.G. Lee, R.C. Gonzales, and K.S. Fu). IEEE Computer Society Press, 1986 (2nd edition): Washington, D.C.
- Bonasso, P., Firby, J., Gat, E., Kortenkamp, D., Miller, D, and Slack, M. 1997. Experiences with an Architecture for Intelligent, Reactive Agents. *Journal of Experimental Theory of Artificial Intelligence*. 9: 237-256.
- Virtual Reality: Scientific and Technological Challenges, a report of the Committee on Virtual Reality Research & Development (Chr., N. Durlach), National Research Council. NAS Press, 1994: Washington D.C.
- Bonasso, R. P., Kortenkamp, D., and Thronesbery, C. 2003. Intelligent Control of A Water Recovery System: Three years in the Trenches. *AI Magazine* 24 (1): 19-44.
- Space Station/OACT Robotics Technology Study," Vol. 1. (ref: NASA TM B93DSS-039, Oceaneering Space Systems with McDonnell Douglas Aerospace, 1993).
- Bradshaw, J. M., Sierhuis, M., Gawdiak, Y., Thomas, H., Greaves, M. and Clancey, W. J. (2000). Human-Centered Design for the Personal Satellite Assistant, In *International Conference on Human-Computer Interaction in Aeronautics* 2000, Toulouse, France.
- Geometric Uncertainty in Motion Planning: Summary Report and Bibliography, an NSF sponsored workshop, report issued as IRIS TR No. 297, University of Southern California, Los Angeles, CA (Eds., K. Y. Goldberg, M. T. Mason, and A. Requicha), August, 1992.
- Malin, J. T., and Johnson, K. 2003. Information for Successful Interaction with Autonomous Systems. In *Human Interaction with Autonomous Systems in Complex Environments: Papers from the AAAI Spring Symposium*. AAAI Press, Technical Report, SS-03-04, 129-133.
- S. Abhrams and P. K. Allen, "Sensor planning in an active robotic workcell," Proc. DARPA Image Understanding Workshop, January, 1992 (Morgan-Kaufmann).
- Malin, J.T. 2004. Interaction between Autonomous Systems and Anomaly Response Teams. In "Interaction between Humans and Autonomous Systems in Extended Operations: Papers from the AAAI Spring Symposium. AAAI Press, Technical Report, SS-04-03, 133-135.
- J. S. Albus, Brains, Behavior, and Robotics. McGraw-Hill, 1981: New York, NY.
- Malin, J. T.; Johnson, K.,; Molin, A.; and Schreckenghost, D. 2002. Integrated Tools for Mission Operations Teams and Software Agents. In *Aerospace IEEE 2002Conference Proceedings*. IEEE Press.
- J. S. Albus, R. Lumia, and H. McCain, "Hierarchical control of intelligent machines applied to Space Station robots," IEEE Trans. Aerospace and Electronic Systems, Vol. 24, No. 5, pp. 535-541, September, 1988.
- Muscettola, N. P. Nayak, B. Pell, and B. Williams. Remote Agent: To Boldly Go Where No AI System Has Gone Before. *Artificial Intelligence* 103(1-2):5-48, August 1998.

Most Influential Papers (II)

- J. S. Albus and R. Quintero, "Toward a reference model architecture for real-time intelligent control systems (ARTICS)," in Robotics and Manufacturing, Vol. 3 (Proc. ISRAM '90). ASME Press, 1990: New York, NY.
- Rehnmark, F., Bluethmann, W., Huber, E., Rochlis, J., Ambrose, R.O., "Useful Interactions Between Human and Robotic Agents Performing a Cooperative Assembly Task", Proceedings of AIAA Space2003. Long Beach, CA. September, 2003.
- P. G. Backes and K. S. Tso, "UMI: an interactive supervisory and shared control system for telerobotics," in Proc. 1990 IEEE Intl. Conf. Robotics and Automation, Cincinnati, OH, May.
- Rich, C.; Sidner, C.L.; Lesh, N.B., "COLLAGEN: Applying Collaborative Discourse Theory to Human-Computer Interaction", *Artificial Intelligence Magazine*, Winter 2001 (Vol 22, Issue 4, pps 15-25, TR2000-38)
- P. Backes, J. Beahan, and B. Bon, "Interactive command building and sequencing for supervised autonomy," in Proc. 1993 IEEE Intl. Conf. Robotics and Automation, Atlanta, May.
- Paul Scerri, David V. Pynadath, Milind Tambe: Why the elf acted autonomously: towards a theory of adjustable autonomy. *AAMAS 2002*: 857-864
- A. K. Bejczy and Z. F. Szakaly, "An 8 d.o.f. dual arm system for advanced teleoperation performance experiments," in Proc. SOAR `91 Symposium (Space Operations, Applications, and Research), Houston, TX, July 1991.
- Schreckenghost D.; Ryan, D.; Thronesbery, C.; Bonasso, P.; and Poirot, D. Intelligent control of life support systems for space habitats. *AAAI IAAI* 1998. Madison, WI. July 1998. 2) Toward Learning Robots (Ed., W. Van de Welde). The MIT Press, 1993: Cambridge, MA.
- A. K. Bejczy, P. Fiorini, W. S. Kim, and P. Schenker, "An integrated operator interface for advanced teleoperation with time-delay," in Proc. 1994 IEEE/RSJ/GI Intl. Conf. IROS, Munich, Germany, September, 1994.
- R. A. Brooks, "Elephants don't play chess," pp. 3-16, in Designing Autonomous Agents: Theory and Practice from Biology to Engineering and Back (Ed., P. Maes). The MIT Press, 1990: Cambridge, MA.
- R. A. Brooks, "Building brains for bodies," in Autonomous Robots, Vol. 1, no. 1, pp. 7-26, November, 1994.
- R. A. Brooks, "Intelligence without representation," and P. S. Rosenbloom, J. E. Laird, A. Newell, and R. McCarl, "A preliminary analysis of the Soar architecture as basis for general intelligence," in The Foundations of Artificial Intelligence (Ed., D. Kirsch). The MIT Press, 1992: Cambridge, MA.
- T. Brooks, I. Ince, and G. Lee, "Vision issues for space teleoperation assembly and servicing (VISTAS)," Rept. No. STX/ROB/91-01, (NASA Contract #NAS-5-30440), STX Corporation, Lanham, MD, January, 1991.
- B. K. Christensen, W.R. Drotning, and S. Thornborg, "Graphical model based control of intelligent robot systems," Proc. 1991 IEEE Intl. Conf. Systems, Man, and Cybernetics, Sacramento, CA, May.

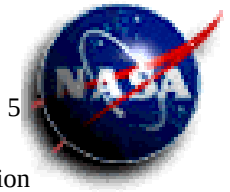
Most Influential Papers (III)

- L. Conway, R. Volz, and M. Walker, "Teleautonomous systems: methods and architectures for intermingling autonomous and telerobot technology," in Proc. 1987 IEEE Intl. Conf. Robotics and Automation, Raleigh, NC, March.
- H. Das, P. S. Schenker, H. Zak and A. K. Bejczy, "Teleoperated satellite repair experiments," in Proc. 1992 IEEE-RSJ Intl. Conf. IROS, Raleigh-Durham, NC, July.
- H. Das,, H. Zak, W. S. Kim, A. K. Bejczy, and P. S. Schenker, "Operator performance with alternative manual modes of control," Presence, vol. 1, no. 2, pp. 201-218, Spring 1992.
- P. Fiorini, A. K. Bejczy, and P. S. Schenker, "Integrated interface for advanced teleoperation," IEEE Control Systems, Vol. 13, no. 5, pp. 15-20, October, 1993.
- A. M. Flynn, R. A. Brooks, W.M. Wells, III, D. S. Barrett, "Intelligence for miniature robots," Sensors and Actuators, Vol. 20, pp. 187-196, 1989.
- J. Funda, T. S. Lindsay, and R. P. Paul, "Teleprogramming: toward delay-invariant remote manipulation," Presence, Vol. 1, no. 1, pp. 29-44, 1992.
- G. Harbaugh, "An operational perspective on the use of telerobotic systems in manned spaceflight," in Proc. AIAA Conf. Space Programs and Technologies, Paper 92-1450, Huntsville, AL, March, 1992.
- S. Hirai, T. Sato and T. Matsui, "Intelligent and cooperative control of telerobot tasks," IEEE Control Systems Magazine, pp. 51-56, February, 1992.
- G. Hirzinger, B. Brunner, J. Dietrich, and J. Hendl, "Sensor-based space robotics -- ROTEX and its telerobotic features," IEEE Trans. Robotics and Autom., Vol. 9, No. 5, pp. 649-663, October 1993.
- G. Hirzinger, J. Heindl, K. Landzettel, and B. Brunner, "Multisensory shared autonomy -- a key issue in the space robot technology experiment ROTEX," Proc. 1993 IEEE/RSJ Intl. Conf. IROS, Raleigh-Durham, NC, July.
- W. S. Kim and P. S. Schenker, "Teleoperation training simulator with visual and kinesthetic force reality," in Human Vision, Visual Processing, and Visualization, Proc. SPIE 1666, San Jose, CA, February, 1992.
- W. S. Kim, P. S. Schenker, A. K. Bejczy, S. Leake, and S. Ollendorf, "An advanced operator interface design with preview/predictive displays for ground-controlled space telerobotic servicing," in Telemanipulator Technology and Space Robotics, Proc. SPIE 2057, Boston, MA, September, 1993.
- W. S. Kim, P. S. Schenker, A. K. Bejczy and S. Hayati, "Advanced graphic interfaces for telerobotic servicing and inspection," in Proc. 1993 IEEE-RSJ Intl. Conf. IROS, Yokohama, Japan, July.
- W. S. Kim, "Virtual reality calibration for telerobotic servicing," in Proc. 1994 IEEE Intl. Conf. Robotics and Automation, San Diego, CA, May.
- P. Lee, A. K. Bejczy, P. S. Schenker, and B. Hannaford, "Telerobot configuration editor," in Proc. IEEE Intl. Conf. Systems, Man, and Cybernetics, Los Angeles, CA, November, 1990.

Most Influential Papers (IV)

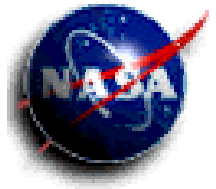
- S. Lee, P. S. Schenker, and J. Park, "Sensor-knowledge-command fusion paradigm for man/machine systems," Proc. IFAC Distributed Intelligence Systems '91, Arlington, VA, August, 1991.
- M. J. MacDonald and R. D. Palmquist, "Graphical programming: on-line robot simulation for telerobotic control," in Proc. Intl. Robots and Vision Automation Conf., Detroit, MI, April, 1993.
- M. Mallem, F. Chavand, and E. Colle, "Computer-assisted visual perception in teleoperated robotics," Robotica, Vol. 10, pp. 93-103, 1992D. McFarland and T. Bosser, Intelligent Behavior in Animals and Robots. The MIT Press, 1993: Cambridge, MA.
- G. T. McKee and P. S. Schenker, "Visual acts for goal-directed vision," in 1995 IEEE Intl. Conf. Robotics and Automation, Nagoya, Japan, May.
- G. T. McKee and P. S. Schenker, "Human-robot cooperation for automated viewing during teleoperation," in 1995 IEEE-RSJ Intl. Conf. IROS, Pittsburgh, PA, August.
- G. T. McKee and P. S. Schenker, "Networked robotics, cooperating agents, and an application to `Visual Acts'," in Proc. IEEE/Intl. Symp. Intell. Control Workshop (Architectures for Semiotic Modeling and Situation Analysis in Large Complex Systems, Orgs.: J. Albus, A. Meystel, D. Pospelov, T. Reader), Monterey, CA, August, 1995
- K. Mochizuki, H. Takemura, and F. Kishino, "Object manipulation and layout in 3-D virtual space using a combination of natural language and pointing," in Sensor Fusion V, Proc. SPIE 1828, Boston, MA, November, 1992.
  E. Oyama, N. Tsunemoto, S. Tachi, and Y. Inoue, "Experimental study on remote manipulation using virtual reality," Presence, Vol. 2, No. 2, pp. 112-124, Spring, 1993.
- E. D. Paljug and P. S. Schenker, "Advanced Teleoperation Control Architecture," in Telemanipulator Technology and Space Robotics, Proc. SPIE 2057, Boston, MA, September, 1993..
- R. P. Paul, C. Sayers, and M. R. Stein, "The theory of teleprogramming," Jrnl. Robotics Soc. Japan, Vol. 11, No. 6, 1993.
- R. J. Popplestone, Y. Liu, and R. Weiss, "A group theoretic approach to assembly planning," AI Magazine, pp. 82-97, Spring 1990.
- J. Rasmussen, "Skills, rules, and knowledge: signals, signs, and symbols, and other distinctions in human performance models," IEEE Trans. Systems, Man, and Cybernetics, SMC-13, pp. 257-266, 1983R. D. Rimey and C. D. Brown, "Sequences, structure, and active vision," in Proc. IEEE Conf. Computer Vision and Pattern Recognition, Lahaina, Maui (HI), 1991.
- T. Sato and S. Hirai, "MEISTER: A model enhanced and skillful teleoperational robot system," in Proc. 4th Intl. Symp. Robotics Rsch. (R. Bolles and B. Roth, Eds.), 1987.
- C. Sayers and R. Paul, "Synthetic fixturing," in Proc. Haptic Interfaces for Virtual Environments and Teleoperator Systems, ASME Winter Annual Meeting, New Orleans, LA, November, 1993.
- P. S. Schenker, A. K. Bejczy, W. S. Kim, and S. Lee, "Advanced man-machine interfaces and control architecture for dexterous teleoperations," in Proc. Oceans `91, pp. 1500-1525, Honolulu, HI, October, 1991.
- P. S. Schenker, "Intelligent robots for space applications," pp. 545-591 in Intelligent Robotic Systems: Analysis, Design, and Programming (S. Tzafestas, Ed.). Marcel Dekker, 1991: New York, NY.

Most Influential Papers (V)



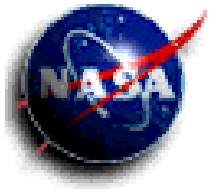
- P. S. Schenker and W. S. Kim, "Remote robotic operations and graphics-based operator interfaces," in Robotics and Manufacturing, Vol. 5 (Proc. ISRAM '94). ASME Press, 1994: New York, NY.
- P. S. Schenker, S. F. Peters, E. D. Paljug, and W.S. Kim, "Intelligent viewing control for robotic and automation systems," in Sensor Fusion VII, Proc. SPIE 2355, Boston, MA, October, 1994.
- P. S. Schenker and S. Hirai, "A US-Japan collaborative robotics research program," in Proc. Third Intl. Symp. on AI, Robotics, and Automation for Space (i-SAIRAS'94), Pasadena, CA, October, 1994.
- B. Schneiderman, Designing the User Interface: Strategies for Effective Human-Computer Interaction. Reading, MA: Addison-Wesley, 1987.
-]T. Sheridan, Telerobotics, Automation, and Human Supervisory Control. The MIT Press, 1992:Cambridge, MA.
- H. A. Simon, "Prediction and prescription in systems modeling," Operations Research, Vol. 38, No. 1, pp. 7-14, Jan-Feb, 1990.
- D. Simon, B. Espiau, and K. Kapellos, "Computer-aided design of a generic robot controller handling reactivity and real-time control issues," IEEE Trans. Control Sys. Techn., Vol. 1, No. 4, December, 1993.
- M.R. Stein and R.P. Paul, "Operator interface for time-delayed teleoperation, with a behavior-based controller," Proc. IEEE Intl. Conf. Robotics & Automation, San Diego, CA, May, 1994.
- Matthew R. Stein, Behavior-Based Control for Time-Delayed Teleoperation, Ph.D. Thesis (April, 1994), The University of Pennsylvania, Philadelphia (Advisor: R.P. Paul; NASA Technical Advisor: P. S. Schenker, Jet Propulsion Laboratory).
- M. Stein, R. Paul, E. Paljug, and P. Schenker, "A cross-country teleprogramming experiment," in 1995 IEEE-RSJ Intl. Conf. IROS, Pittsburgh, PA, August.
- T. Takahashi and H. Ogata, "Robotic assembly operations based on task-level teaching in virtual reality," in Proc. 1992 IEEE Intl. Conf. Robotics and Automation, Nice, France, May.
- K. A. Tarabanis, P. K. Allen, and R. Y. Tsai, "A survey of sensor planning in computer vision," IEEE Trans. Robotics and Autom., Vol. 11, no. 1, pp. 84-104, February, 1995.
- K. J. Vicente and J. Rasmussen, "Ecological interface design: theoretical foundations," IEEE Trans. Systems, Man, and Cybernetics, SMC-22, pp. 589-606, 1992.
- Y. Wakita, S. Hirai and T. Kino, "Automatic camera- work control for intelligent monitoring of telerobotic tasks," in Proc. 1992 IEEE/RSJ Intl. Conf. IROS, Raleigh-Durham, NC, July.
- Y. Wakita and S. Hirai, "Hierarchical control of a visual monitoring system for telerobot tasks," in Proc. 1993 IEEE/RSJ Intl. Conf. IROS, Yokohama, Japan, July.
- Y. Wakita, S. Hirai, K. Machida, S. Peters, E. Paljug, and P. Schenker, "Telerobotic task execution over Internet," submitted to 1995 IEEE-RSJ Intl. Conf. IROS, Pittsburgh, PA, August.

Major Unsolved Problems



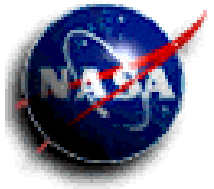
- "Human Equivalent" operations:
  - driving over rough terrain,
  - "seeing" interesting scientific phenomena,
  - manipulating objects,
  - autonomous drilling, digging, excavation
  - responding to voice input and human gesture
  - diagnosing anomalies
  - responding to emergencies
  - keeping the system safe

Research Goals



- Approach the performance of a human teleoperating driver with zero time delay in driving over rough natural terrain.
- Approach the performance of a human in performing dexterous manipulation of samples or tools, drilling/digging, etc.
- Approach the performance of a human in performing real-time diagnosis and recovery from anomalous conditions.

Major Accomplishments in Other Countries



- Russia (the Soviet Union) built the Lunakhod rovers and flew them to the moon (early 1970's)
- Canada built RMS, SRMS, and SPDM (early 1980s to current).
- Germany (Herzinger) built and flew ROTEX on the Space Shuttle - the first robot designed for time-delayed manipulation (1993)
- Japan built and flew the ETS-VII satellite with "model-based telemanipulation", "Robustness against Modeling Errors", and "Compact 6-DOF Haptic Interface" (1997)

International Cooperation

- JPL (A. Bejczy) collaborated with Herzinger on ROTEX
- JPL and JSC collaborated with Japan (NASDA) on ETS-VII.
- Others ?