The NIST Real-time Control System (RCS)
An Applications Survey

by
James S. Albus
Chief, Intelligent Systems Division
National Institute of Standards and Technology

Abstract

The Real-time Control System (RCS) architecture developed at NIST and elsewhere over the past two decades [1] defines a canonical form for a nested intelligent control system. The RCS architecture consists of a hierarchically layered set of processing modules connected together by a network of communications pathways. The primary distinguishing feature of the layers is the bandwidth of the control loops. The characteristic bandwidth of each level is determined by the spatial and temporal integration window of filters, the temporal frequency of signals and events, the spatial frequency of patterns, and the planning horizon and granularity of the planners that operate at each level. At each level, tasks are decomposed into sequential subtasks, to be performed by cooperating sets of subordinate agents. Signals from sensors are filtered and correlated with spatial and temporal features that are relevant to the control function being implemented at that level.

The four basic types of processing modules from which the RCS architecture is built are:

1) Behavior Generating (BG) modules

BG modules contain job assignment, planning, and control algorithms. These embody knowledge about how to perform tasks -- i.e., how to decompose tasks into subtasks that subordinate agents know how to execute. BG modules can accommodate a variety of planning algorithms, from simple table look-up of pre-computed plans, to real-time search of configuration space, or game theoretic algorithms for multi-agent cooperating and competitive groups. Planning horizons at high levels may span months or years, while planning horizons at the bottom level typically are less than 50 milliseconds. Control loop bandwidth at each level is typically at least ten times the reciprocal of the planning horizon at that level.

2) World Modeling (WM) modules

The WM modules model the state space of the problem domain. They contain information storage and retrieval mechanisms, as well as algorithms for transforming information from one coordinate system to another. WM modules use dynamic models to generate expectations, and predict the results of current and future actions. WM modules may contain recursive estimation algorithms and processes that compute lists of attributes from images, graphics engines that generate images from symbolic lists, and storage and retrieval algorithms that perform and maintain both short term and long term memory about features, surfaces, objects, and groups. The WM module maintains a knowledge database (KD), acts as a question answering system, and uses information from the knowledge database to predict or simulate the future.

3) Sensory Processing (SP) modules

SP modules process data from visual, auditory, tactile, proprioceptive, taste, or smell sensors. SP modules contain filtering, masking, differencing, correlation, matching, and recursive estimation algorithms, as well as feature detection and pattern recognition algorithms. Interactions between WM and SP modules can generate a variety of filtering and detection processes such as Kalman filtering and recursive estimation, Fourier transforms, and phase lock loops. Vision system SP modules process images to detect brightness, color, and range discontinuities, optical flow, stereo disparity, and utilize a variety of signal detection and pattern recognition algorithms to analyze scenes and compute information needed for manipulation, locomotion, and spatial-temporal reasoning.

4) Value Judgment (VJ) modules
VJ modules contain algorithms for computing cost, risk, and benefit, for evaluating states and situations, and alternatives courses of action for estimating the reliability of state estimations, and for assigning cost-benefit values to objects and events. VJ modules may compute Beysian and Dempster-Schafer statistics on information about the world based on the correlation and variance between observations and predictions.

The world modeling module maintains a set of:

Knowledge Database (KD) modules
KD modules consist of data structures that contain state variables, iconic images, and symbolic frames containing lists of attributes. Information in the KD includes knowledge about entities and events, and about how the world behaves, both logically and dynamically. The KD contains both short term and long term memory elements. The KD is typically implemented in a distributed fashion, suitable for real-time data retrieval and update.

The entire system is interconnected by:

A communication system that conveys messages between the various modules
The communication system provides a network of pathways that transmits messages between the various processing and database modules. The communications system richly, but not completely, interconnects the modules, i.e. every module is not connected to every other module.

The various modules in the RCS architecture act as a collection of intelligent agents (or software objects), sending and receiving messages to and from each other. These messages convey commands and requests, and return status.

The RCS architecture has evolved over the past two decades from a rather simple robot control schema to a reference model architecture for intelligent system design. From the beginning, RCS has represented a conscious attempt to emulate the function and structure of the neurological machinery in the brain. Each RCS module has properties that are known, or hypothesized, to exist in the brain. For example, RCS modules may be constructed from neural nets such as CMAC [2] that compute arithmetic and/or logical functions on a set of inputs to produce a set of output state variables. These can be carried over communications pathways to other functional modules that may use them to perform further functional computations, or to generate addresses, or to store information in memory for latter use. RCS functional modules may add, subtract, multiply, differentiate, integrate, compute correlation functions, recognize patterns, generate names or addresses of symbolic representations, or perform planning functions at a hierarchy of levels. In its most complete theoretical form, the RCS reference model architecture provides a framework for integrating concepts from artificial intelligence, machine vision, robotics, computer science, control theory, operations research, game theory, signal processing, filtering, and communications theory.

The RCS architecture has been used in the implementation of a number of experimental projects.

These include:

1) A Horizontal Machining Workstation
This project was part of the NBS Automated Manufacturing Research Facility (AMRF). It included a sensory-interactive real-time control system for a robot integrated with a structured light machine vision system, a machine tool, an automatic fixturing system, a pallet shuttle and a material buffering system. The robot included a quick change wrist, a part handling gripper

with tactile sensors, and a tool handling gripper for loading and unloading tools in the machine tool magazine. Plans were represented as state-tables, and a wide variety of sensory interactive behaviors were demonstrated. These included locating and recognizing parts and part orientation of unoriented parts presented in trays, and automatically generating part handling sequences for part and tool loading and unloading. [3]

2) A Cleaning and Deburring Workstation

This project was also part of the AMRF. It included two robots, a set of buffing wheels, a part washing/drying machine, and a variety of abrasive brushes. Part geometry was input from a CAD database. Deburring tool paths were automatically planned from knowledge of the part geometry plus operator input indicating which edges were to be deburred. Deburring parameters such as forces and feed rates were also selected from a menu by the operator. Part handling sequences were planned automatically for loading parts in a vise, and turning parts over to permit tool and gripper access. Force sensors and force control algorithms were used during task execution to modify the planned paths so as to compensate for inaccuracies in robot kinematics and dynamics. [4]

3) An Advanced Deburring and Chamfering System

This project is currently underway. The project integrates off-line programming, real-time control, and active tool technologies to automatically place precision chamfers on complex parts manufactured from hard materials such as aircraft jet engine components. The workstation consists of a force-sensitive active tool integrated with a 6 degree-of-freedom robot and an indexing table used for part manipulation. The active tool, the Chamfering and Deburring End-of-arm Tool (CADET), incorporates actuators and force sensors to provide control over cutting force and tool stiffness at the part edges. Part geometry is derived from standard IGES CAD data formats. Edge selection is performed by a human operator. Required tool force is automatically generated by formula using the cutting depth, feeds, and speeds inputted by the operator. A prototype production cell will be installed at Pratt & Whitney's East Hartford, CT site upon completion of the project. [5]

4) **NBS/NASA Standard Reference Model Architecture for the Space Station Telerobotic Servicer (NASREM)**

This project was funded by NASA Goddard Space Flight Center. NASREM was used by Martin Marietta to develop the control system for the space station telerobotic servicer. Algorithms were developed for force servoing, impedance control, and real-time image processing of telerobotic systems at NIST, Martin Marietta, Lockheed, Goddard, and in a number of university and industry labs in the United States and Europe. [6]

5) An architecture for Coal Mining Automation

This project effectively transferred the RCS architecture and methodology to a large team of researchers in the US Bureau of Mines who are tasked with developing prototype coal mining automation sensors and systems and transferring such systems, in turn, to the mining industry. A comprehensive mining scenario was developed starting with a map of the region to be excavated, the machines to be controlled, and the mining procedures to be applied. Based on this scenario, an intelligent control system with simulation and animation was designed, built, and demonstrated. The same control system was later demonstrated with an actual mining machine and sensors. [7]

6) A nuclear submarine maneuvering system

This project demonstrated the design and implementation in simulation of maneuvering and engineering support systems for a 637 class nuclear submarine. The maneuvering system involves an automatic steering, trim, speed, and depth control system. The system demonstrated the ability to execute a lengthy and complex mission involving transit of the

Bering Straits under ice. Ice avoidance sonar signals were integrated into a local map using a CMAC neural network memory model. Steering and depth control algorithms were developed that enabled the sub to avoid hitting either the bottom or the ice while detecting and compensating for random salinity changes under the ice by making trim and ballast adjustments. The engineering support system demonstrated the ability to respond to a lubrication oil fire by reconfiguring ventilation systems, rising in depth to snorkel level, and engaging the diesel engines for emergency propulsion. [8]

7) A control system for a U.S. Postal Service Automated Stamp Distribution Center.
This system demonstrated the ability to route packages through a series of carousels, conveyors, and storage bins, to maintain precise inventory control, provide security, and generate maintenance diagnostics in the case of system failure. The distribution center was designed and tested first in simulation, and then implemented as a full scale system. The system contained over 220 actuators, 300 sensors, and ten operator workstations.   An even larger and more complex RCS system for controlling a general mail facility is still under development. [9]

8) A control system for Multiple Autonomous Undersea Vehicles
This systems was developed for controlling a pair of experimental vehicles designed and built by the University of New Hampshire. The RCS control system included a real-time path planner for obstacle avoidance, and a real-time map builder for constructing a topological map of the bottom. A series of tests was conducted in Lake Winnipasaki during the fall of 1987. [10]

9) An RCS system for remote driving
This system was implemented on an Army HMMWV light truck. One version of the system enables the vehicle to be driven remotely by an operator using TV images transmitted from the vehicle to an operator control station. This version has a retrotraverse mode that permits the vehicle to autonomously retrace paths previously traversed under remote control, using an inertial guidance system.

A second version of this RCS system has demonstrated the ability to drive the HMMWV automatically using TV images processed through a machine vision system with a real-time model matching algorithm for tracking lane markings.   The RCS real-time vision processing system has enabled this vehicle to drive automatically at speeds up to 100 km per hour on the highway, and at speeds up to 50 km miles per hour on a winding test track used by the county police for driver-training. [11]

10) An Open Architecture Enhanced Machine Controller
The RCS reference model is being used as the basis for an open architecture Enhanced Machine Controller (EMC) for machine tools, robots, and coordinate measuring machines. The EMC combines NASREM with the Specification for an Open System Architecture Standard (SOSAS) developed under the Next Generation Controller program sponsored by the Air Force and National Center for Manufacturing Sciences. In cooperation with the DoE TEAM program, EMC functional modules have been defined, and Application Programming Interfaces (APIs) are being defined for sending messages between the functional modules. A prototype machine tool controller is being installed in a General Motors plant as part of the DoE-TEAM/NIST-EMC government/industry consortium. The goal of this effort is to define a set of standard application programming interfaces for open architecture controllers. [12]

All of the projects listed above that have used the RCS architecture have implemented only a subset of the features of the most advanced theoretical form of the RCS reference model architecture [13]. This is because the RCS theoretical development has remained well beyond over what has been possible to implement, given programmatic limitations in funding.

Current work at NIST and elsewhere is pursuing more complex implementations of RCS. For example, efforts to incorporate human operator interfaces into the RCS architecture that began with NASREM have continued with the Air Force/JPL/NIST Universal Telerobotic Architecture Project (UTAP) [14], and the NIST RoboCrane. Work is also under way to integrate the RCS architecture with the Manufacturing Systems Integration (MSI) factory control architecture, and the Quality In Automation (QIA) architecture. [15] When complete, this joint architecture will define a reference model architecture for manufacturing that extends all the way from the servomechanism level to the enterprise integration level. Work is also in progress to develop an engineering design methodology and a set of software engineering tools for developing RCS systems [16].

References

[1]
Barbera, A.J., Albus, J.S. and Fitzgerald, M.L., "Hierarchical Control of Robots using Microcomputers," Proceedings of the 9th International Symposium on Industrial Robots, Washington, DC, March 13-15, 1979

Albus, J.S., McLean, C.R., Barbera, A.J. and Fitzgerald, M.L., "Architecture for Real-Time Sensory-Interactive Control of Robots in a Manufacturing Facility," Proceedings of the Fourth IFAC/IFIP Symposium -- Information Control Problems in Manufacturing Technology, Gaithersburg, MD, October 26-28, 1982

Albus, J.S., "Outline for a Theory of Intelligence," IEEE Transactions on Systems, Man and Cybernetics, Vol. 21, No. 3, pgs. 473-509, May/June 1991

Albus, J.S., "A Reference Model Architecture for Intelligent Systems Design," In *An Introduction to Intelligent and Autonomous Control,* (Antsaklis, P.J., and Passino, K.M. eds.)

[2]
Albus, J.S,. "New Approach to Manipulator Control: The Cerebellar Model Articulation Controller (CMAC)," Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control, September 1975

Albus, J.S. "Data Storage in the Cerebellar Model Articulation Controller (CMAC)," Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control, September 1975

[3]
Albus, J.S., McLean, C.R., Barbera, A.J. and Fitzgerald, M.L., "Hierarchical Control for Robots in an Automated Factory," Proceedings of the 13th International Symposium on Industrial Robots/Robots 7, Chicago, IL, April 18-21, 1983

Barbera, A.J., Fitzgerald, M.L., Albus, J.S. and Haynes, L.S., "RCS: The NBS Real-Time Control System," Proceedings of the Robots 8 Conference and Exposition, Volume 2 - Future Considerations, Detroit, MI, June 4-7, 1984

Bunch, W.R., Fishman, D.B., Scott, H.A., "Integration of Material Buffering Devices in an Automated Factory," Proceedings of the Robotics and Factories of the Future, San Diego, CA, July 28-31, 1987

Fishman, D., "The High Level Machine-Tool Control System, "NBSIR 88-3836, National

Institute of Standards and Technology, Gaithersburg, MD, August 1988

Rippey, W.G., Scott, H.A., “Real-Time Control in a Machining Workstation,” presented at Numerical Control Society’s 20th Annual Meeting and Technical Conference, Cincinnati, PH, April 10-13, 1983

Scott, H.A., Strouse, K., “Workstation Control in a Computer Integrated Manufacturing System,” Autofact VI, Anehiem, CA, October 4, 1984

Wavering, A.J. and Fiala, J.C., “Real-Time Control System of the Horizontal Workstation Robot,” NBSIR 88-3692, National Institute of Standards and Technology, Gaithersburg, MD, December 1987

[4]
Murphy, K.N., Norcross, R.J. and Proctor, F.M., “CAD Directed Robotic Deburring,” Proceedings of the Second International Symposium on Robotics and Manufacturing Research, Education, and Applications, Albuquerque, NM, November 16-18, 1988

Norcross, R.J., “Workstation Controller of the Cleaning and Deburring Workstation,” NISTIR 89-4046, Gaithersburg, MD, February 1989

Proctor, F.M., Murphy, K.N. and Norcross, R.J., “Automating Robot Programming in the Cleaning and Deburring Workstation of the AMRF,” Proceedings of the SME Conference on Deburring and Surface Condition '89, San Diego, CA, February 13-16, 1989

Murphy, K.N., Norcross, R.J. and Proctor, F.M., “CAD Directed Robotic Deburring,” Proceedings of the Second International Symposium on Robotics and Manufacturing Research, Education, and Applications, Albuquerque, NM, November 16-18, 1988

[5]
Stouffer, K., Michaloski, J., Russell, R. and Proctor, F., “ADACS - An Automated System for Part Finishing,” NISTIR 5171, National Institute of Standards and Technology, Gaithersburg, MD, April 1993, and Proceedings of the IECON ‘93 International Conference on Industrial Electronics, Control and Instrumentation, Maui, Hawaii, Nov. 15-19, 1993

Stouffer, K., “NIST Integrated CAD into Robotic Chamfering,” To be published in a future issue of CADENCE Magazine

Proctor, F.M., and Murphy, K.N., “Advanced Deburring System Technology” Winter Annual Meeting of ASME, San Francisco, CA, December 10-15, 1989

[6]
Albus, J.S., McCain, H.G. and Lumia, R., “NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM),” NISTTN 1235, 1989 Ed, National Institute of Standards and Technology, Gaithersburg, MD, April 1989 (supersedes NBS Technical Note 1235, July 1987)

Albus, J.S., Lumia, R., Fiala, J. and Wavering, A., “NASREM -- The NASA/NBS Standard Reference Model for Telerobot Control System Architecture,” Proceedings of the 20th International Symposium on Industrial Robots, Tokyo, Japan, October 4-6, 1989

[7]
Albus, J.S., Quintero, R., Huang, H.M. and Roche, M. , “Mining Automation Real-Time Control

System Architecture Standard Reference Model (MASREM)," NISTTN 1261, Volume 1, National Institute of Standards and Technology, Gaithersburg, MD, May 1989

Huang, H.M., Quintero, R. and Albus, J.S., "A Reference Model, Design Approach, and Development Illustration toward Hierarchical Real-Time System Control for Coal Mining Operations," Advances in Control & Dynamic Systems, Academic Press, July 1991

Horst, J.A. and Barbera, A.J., "An Intelligent Control System for a Cutting Operation of a Continuous Mining Machine," NISTIR 5142, National Institute of Standards and Technology, Gaithersburg, MD, March 1993

Huang, H.M., Horst, J. and Quintero, R., "An Algorithm for Real-Time Motion Control of a Continuous Mining Machine'", Journal for Intelligent and Robotic Systems 5: 79-99, Kluwer Academic Publishers, Netherlands, 1992

Horst, J.A., "Coal extraction using RCS," Proceedings of the 8th IEEE International Symposium on Intelligent Control, Chicago, IL, August 24-27, 1993

Horst, J.A., "Servo Control of a Coal Mining Machine Appendage and Integration into a Real-Time Control System (RCS) Design," Proceedings of the Summer Computer Simulation Conference, 1994

[8]
Huang, H.M., Hira, R. and Feldman, P., "A Submarine Simulator Driven by a Hierarchical Real-Time Control System Architecture," NISTIR 4875, National Institute of Standards and Technology, Gaithersburg, MD, July 1992

Huang, H.M., Hira, R. and Feldman, P., "A Submarine Maneuvering System Demonstration Using a Generic Real-Time Control System (RCS) Reference Model," Proceedings of the Summer Computer Simulation Conference '92, Reno, NV, July 27-29, 1992

Huang, H.M., Hira, R., Quintero, R. and Barbera, A., "Applying the NIST Real-Time Control System Reference Model to Submarine Automation: A Maneuvering System Demonstration," NISTIR 5126, Gaithersburg, MD, February 1993

Huang, H.M., Hira, R. and Quintero, R., "A Submarine Maneuvering System Demonstration Based on the NIST Real-Time Control System Reference Model," Proceedings of the 8th IEEE International Symposium on Intelligent Control, Chicago, IL, August 24-27, 1993

[9]
Stamp Distribution Network, USPS Contract Number 104230-91-C-3127 Final Report, Advanced Technology & Research Corp, Burtonsville, MD, 20866-1172

[10]
Albus, J.S. and Blidberg, D.R., "Control System Architecture for Multiple Autonomous Undersea Vehicles (MAUV)," Proceedings of the Fifth International Symposium on Unmanned, Untethered Submersible Technology, Merrimack, NH, June 22-24, 1987

Herman, M. and Albus, J.S., "Real-Time Hierarchical Planning for Multiple Mobile Robots," Proceedings of the DARPA Knowledge-Based Planning Workshop, Austin, TX, December 8-10, 1987

Herman, M. and Albus, J.S., "Overview of the Multiple Autonomous Underwater Vehicles

(MAUV) Project," 1988 IEEE International Conference on Robotics and Automation, Philadelphia, PA, April 1988

Albus, J.S., "System Description and Design Architecture for Multiple Autonomous Undersea Vehicles," NISTTN 1251, National Institute of Standards and Technology, Gaithersburg, MD, September 1988

[11]
Herman, M., Albus, J.S. and Hong, T.H., "Real-Time Vision for Autonomous and Teleoperated Control of Unmanned Vehicles," Active Perception and Robot Vision, Sood, A., ed., Springer-Verlag: Heidelberg, 1991

Herman, M., Raviv, D., Schneiderman, H. and Nashman, M. , "Visual Road Following Without 3-D Reconstruction," Proceedings of the SPIE 22nd Applied Imagery Pattern Recognition Workshop, Vol. 2103, Washington, DC, October 1993

Murphy, K., Juberts, M., Legowik, S., Nashman, M., Schneiderman, H., Scott, H. and Szabo, S., "Ground Vehicle Control at NIST: from Teleoperation to Autonomy," Published at the Seventh Annual Space Operations, Applications, and Research Symposium, Houston, TX, August 3-5, 1993

Juberts, M., Murphy, K., Nashman, M., Schneiderman, H., Scott, H. and Szabo, S. , "Development and Test Results for a Vision-Based Approach to AVCS," Proceedings of the 26th International Symposium on Automotive Technology and Automation, Aachen, Germany, September 1993

Nashman, M. and Schneiderman, H. , "Real-Time Visual Processing for Autonomous Driving," Proceedings of the IEEE Intelligent Vehicles '93 Conference, Tokyo, Japan, July 14-16, 1993

Schneiderman, H., Nashman, M. and Lumia, R. , "Model-based vision for car following," Proceedings of the SPIE Sensor Fusion VI, Boston, MA, September 1993

Schneiderman, H. and Nashman, M., "Visual Tracking for Autonomous Driving," To be published in IEEE Transactions on Robotics and Automation

Szabo, S., Scott, H.A., Murphy, K.N. and Legowik, S.A., "Control System Architecture for a Remotely Operated Unmanned Land Vehicle," Proceedings of the 5th IEEE International Symposium on Intelligent Control, Philadelphia, PA, September 1990

[12]
Proctor, F. and Michaloski, J., "Enhanced Machine Controller Architecture Overview," NISTIR 5331, National Institute of Standards and Technology, Gaithersburg, MD, December, 1993

Albus, J.S., Quintero, R., Proctor, F., Michaloski, J., Dagalakis, N. and Tarnoff, N., "NIST Support to the Next Generation Controller Program: 1991 Final Technical Report," NISTIR 4888, National Institute of Standards and Technology, Gaithersburg, MD, August 1992

Proctor, F.M., Damazo, B., Yang, C. and Frechette, S. , "Open Architectures for Machine Control," NISTIR 5307, National Institute of Standards and Technology, Gaithersburg, MD, December 1993

[13]
Albus, J.S., "A Reference Model Architecture for Intelligent Systems Design" NISTIR 5502, National Institute of Standards and Technology, Gaithersburg, MD, 1994

[14]
J. L. Michaloski, P. G. Backes, and R. Lumia, "Characterization of Interface Properties for Generic Control Architectures," submitted to 1995 IEEE Int'l Conf. on Robotics and Automation, Nagoya, Japan, May 21-27, 1995.

R. Lumia, J. L. Michaloski, R. Russell, T. E. Wheatley, P. G. Backes, S. Lee, R. Steele, "Unified Telerobotic Architecture Project (UTAP) Interface Document - Draft", White Paper, National Institute of Standards and Technology, Bldg. 220, Rm. B127, Gaithersburg, MD 20899, June 18, 1994.

[15]
Kramer, T.J., Senehi, M.K. "Feasibility Report: Reference Architecture for Machine Control Systems Integration, NISTIR 5297, National Institute of Standards and Technology, Gaithersburg, MD,1993

Senehi, M.K., Kramer, T.J., Michaloski, J., Quintero, R., Ray, S.R., Rippey, W.G., Wallace, S., "Reference Architecture for Machine Control Systems Integration: Interim Report" NISTIR 5517, National Institute of Standards and Technology, Gaithersburg, MD, 1994

[16]
Michaloski, J. and Wheatley, T., "Design Principles for a Real-Time Robot Control System," Proceedings of the IEEE International Conference on Systems Engineering, Pittsburgh, PA, August 1990

Quintero, R., Barbera, A.J., "A Real-Time Control System Methodology for Developing Intelligent Control Systems," NISTIR 4936, National Institute of Standards and Technology, Gaithersburg, MD, 1992

Quintero, R., Barbera, A.J., "A Software Template Approach to Building Complex Large-Scale Intelligent Control Systems," Proceeding of the 8th IEEE International Symposium on Intelligent Control, Chicago, IL, September 25-27, 1993