ROBOTICS RESEARCH

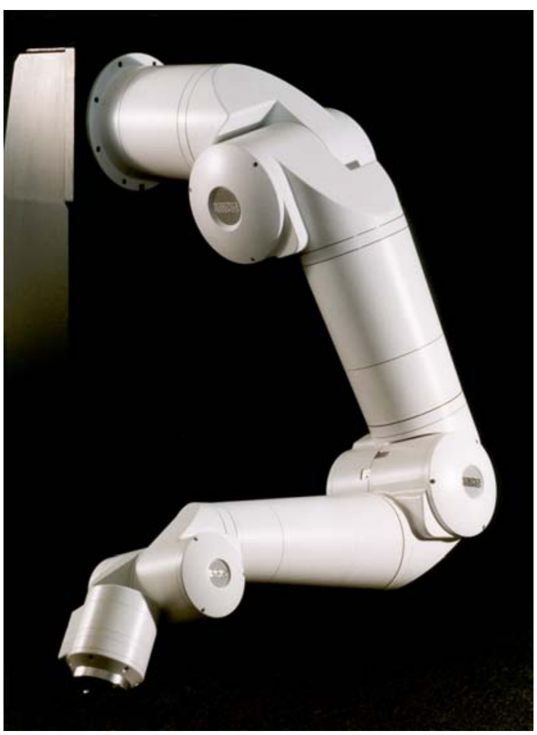
Dexterous Manipulators and Advanced Control Systems

Robotics Research Corporation is a worldwide supplier of advanced technology robotic manipulators and control products. RRC offers a line of highly dexterous, force/position controlled, modular, electric manipulators and an open architecture control system that are in wide use by U.S. federal agencies, government contractors, industrial corporations and universities working on man-equivalent robotic and telerobotic applications.

Technology:

Robotics Research's manipulator products are widely acknowledged to be the state-of-the-art in the field. The company's kinematically redundant, electric robots offer high bandwidth force control, unparalleled 'human-like' dexterity with a very high degree of precision in a compact, lightweight package. These highly anthropomorphic devices are characterized by a number of proprietary features, which make them uniquely suited for the most demanding industrial and scientific applications, including:

- Modular construction, which enables the assembly of a wide range of robot configurations from the same set of standard hardware and software components.
- Semiconductor torque transducers are built into each joint to permit direct torque control.
- Powerful motion control algorithms, which handle redundant kinematics, singularity negotiation and force control.
- Open architecture, motion control system, which allows the user to operate the manipulator in either robotic or teleoperated modes using Cartesian toolpoint coordinates or joint position, velocity, current, and torque commands. The system can be configured to control virtually any robotic manipulator.



K-1207i: 7 DOF Manipulator

K-2017: 17 DOF Manipulator

Key features of the technology are:

Dexterity

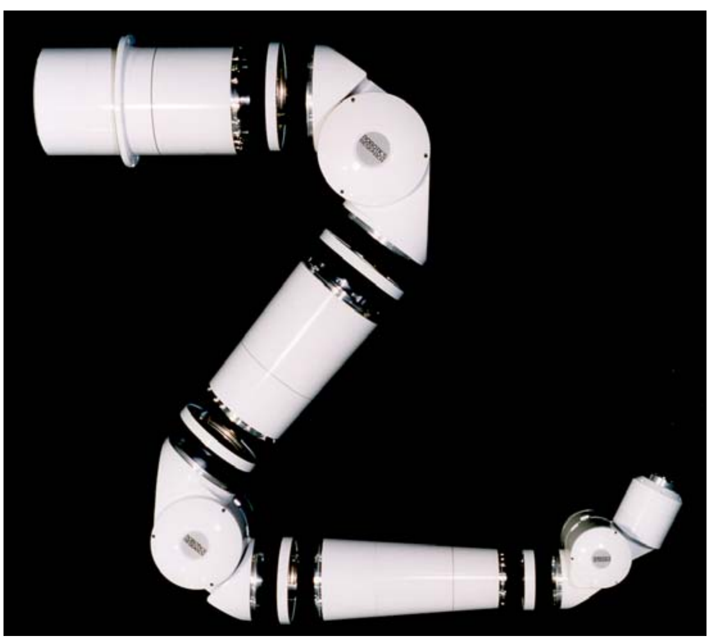
RRC manipulators are kinematically redundant, incorporating seven or more degrees of freedom disposed in a roll-pitch-roll configuration. In combination, this 7 degree-of-freedom (DOF) geometry displays the highest level of dexterity available today in a jointed arm manipulator. This type of arm can position and orient an end effector throughout a complete sphere, with an infinite range of arm poses. While manipulators with fewer degrees of freedom can be produced using our standard modules, the increase in dexterity of redundant manipulators is extremely beneficial in increasing part accessibility, avoiding obstacles in the workspace, and greatly simplifying programming.

Precision

RRC manipulators afford positioning repeatability within a standard deviation of 0.05mm. RRC has produced models optimized for positioning resolution with measuring repeatability of 0.01mm in a stable temperature environment.

Modular Arm Construction

RRC manipulator mechanisms are modular. Manipulator configurations are built from a family of modular actuators covering a wide range of torque capacities. This modular construction allows the assembly of manipulators of varying sizes, payloads, kinematic configurations, and redundancy for different applications — all using standard components. In this patented design, each joint module contains a DC brushless motor component set, harmonic drive gear reducer, fail-safe brake, sealed axis bearings, drive output position and torque transducers — all integrated into a lightweight aluminum structure. Each self-contained joint module is attached by quick-disconnect band clamps. Modules can be disconnected within in a minute, which facilitates maintenance and retrofit.

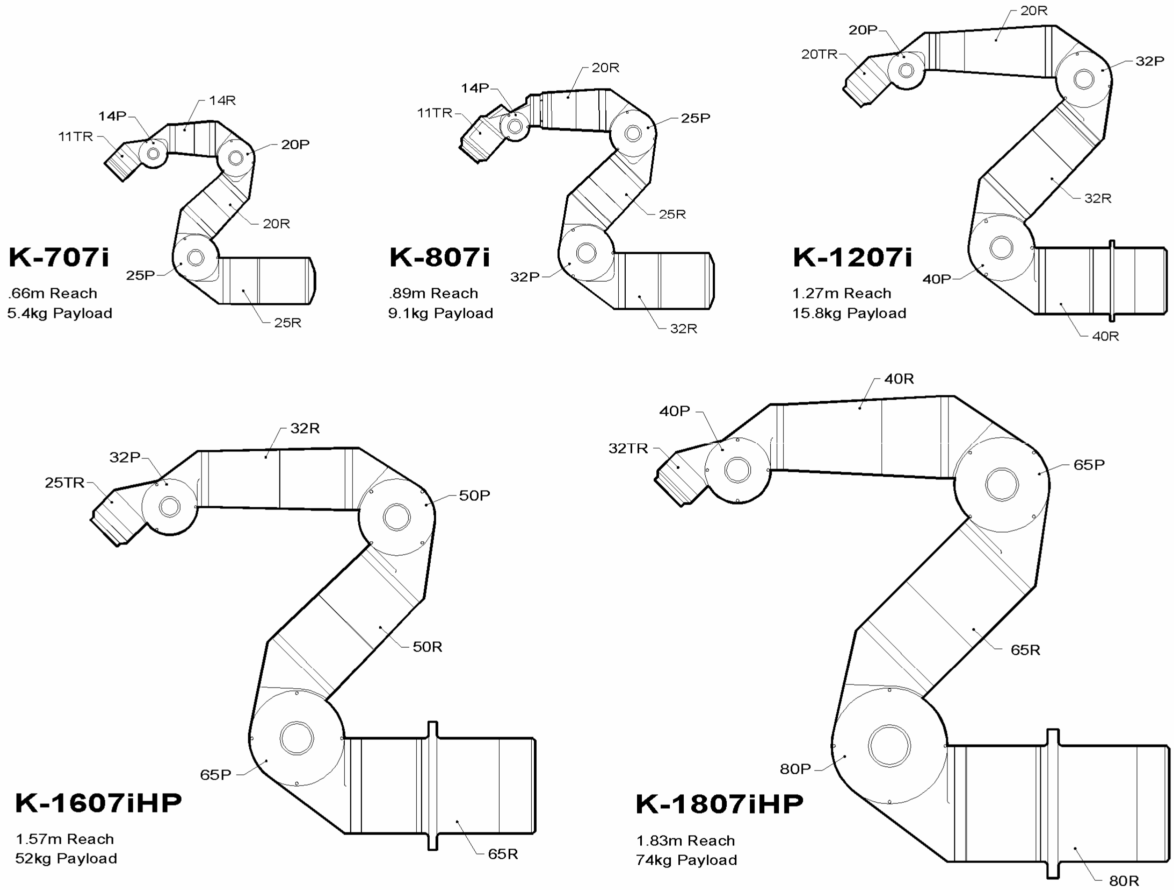


All modules of a particular size are internally identical. The difference between a roll module and a pitch module, for example, is simply the attachments between their adjacent joints. In addition, by selecting different harmonic drive ratios and motor windings, the torque and speed of an actuator package can be tailored to a specific application.

The integration of additional modules to achieve even greater dexterity is readily achievable. Units with as many as 7 axes in series and 17 axes in branching topologies, all operating under the same real-time coordinated control, have been built.

The manipulators incorporate an internal wiring harness that is routed through a centerline wire passage in each joint module. This arrangement produces very little stress on the wiring harness, ensuring long life and virtually eliminating wire related failures. This also eliminates loose external loops of wire that can inadvertently snag on objects in the workplace and makes the system ideal for clean room environments or applications requiring wash down.

Examples of i-Type 7 DOF Manipulator Configurations



Light Weight

RRC manipulators are the lightest electric drive, articulated robotic arms available for a given reach and payload. For instance, the K-1207i model, offering a 1270mm reach from the center of the shoulder pitch to the faceplate and a 15.8kg continuous-duty payload, weighs only 71kg. “Continuous-duty payload” represents the maximum load that the system can handle in any arm pose, indefinitely.

Although light in weight, the manipulators are designed and manufactured to provide the highest degree of reliability in demanding applications and environments. High-strength wrought aluminum structures are employed throughout the design, and the motors and gearing are rated to the most conservative industrial standards to achieve exceptional durability.

Torque-Loop Servo Control

RRC manipulators utilize a patented torque-loop servo control system. The innermost servo control loop is a torque loop. A semiconductor strain gauge array incorporated in each joint actuator is employed to measure and control the joint output torque. Torque loop bandwidths vary depending upon actuator size, but range from 40 to 60Hz. In addition to controlling actuator dynamics and eliminating apparent joint friction, these torque loops can be utilized with impedance control algorithms to achieve extremely high bandwidth force control at the tool without the need for additional hardware.

R2 Distributed Control System

Robotics Research's R2 Distributed Control System (DCS) software provides the most advanced robotic control capabilities in the industry. It employs a component-based, network-centric, hierarchical architecture, which addresses high-level control issues such as operator interfaces, sensor and third party integration, web services, network deployment, and security, while still providing deterministic real-time control. It consists of remotely accessible, deployable, interoperable, self-contained software components, which have well-defined interfaces and behavior and apply system decomposition principles. The R2 DCS components are designed to ensure a reasonable isolation from the supporting middleware, operating system, architecture and implementation, which provides an ideal platform for research and development activities.

The R2 controller can support virtually any robotic mechanism, while providing many advanced features not available on standard industrial robot controls. The mechanism, control hardware and control capabilities are completely configurable through the use of text configuration files. The R2 Control supports four tool contact schemes, namely position with dynamically adjustable servo gains, impedance, compliance and a targeted force control. The real-time layer of the R2 DCS employs a sensory interactive scheme, which permits its upper level controls to dynamically modify any of its low level control parameters, such as the target trajectory position and velocity profile, force control and servo gains, redundancy criteria, etc., on a four millisecond basis.

The R2 Control Software has been packaged as an industrial turnkey controller, which executes under the Windows NT 4.0®, Windows Embedded NT®, Windows 2000®, and Windows XP® operating systems in conjunction with the INtime® real time extension.

The R2 Control consists of two primary components of operation, namely, the INtime real-time component, R2 RTC, and the Windows client-server upper control level component. The R2 RTC provides deterministic, hard real-time control with typical loop times ranging from 1 to 4 milliseconds. This component performs trajectory planning, Cartesian compliance and impedance force control, forward kinematics, inverse kinematics, and advanced heavy deposition welding.

The Windows component of the R2 Control consists of three processes, namely, the R2 Server and two clients, the R2 Master and the R2 SolidWorks simulator. These processes interact with each other on a client-server TCP/IP protocol basis. All controller commands originate from the master client. The master client communicates to the real-time controller (i.e. R2 RTC) via the R2 Server. The standard R2 Controller provides a complete set of Client API calls which permits a third party to implement its own client control.

R2 Kinematic Redundancy Resolution Algorithm

Robotics Research's patented redundancy management algorithm mathematically models a robot as a physically realizable system with an imaginary rotary spring attached to each joint. Each joint spring has a stiffness value and an origin, where no spring force is exerted. The algorithm calculates joint positions based on an objective function of minimum spring energy.

If the robot can physically move to a Cartesian tool position, unique joint positions can be calculated without any mathematical problems. Because the solution is unique, the system is conservative. It will provide the same solution of joint values independent of the approach path to the Cartesian tool position. The algorithm is not limited with respect to a number of redundant degrees of freedom. In fact, the more redundancy a manipulator possesses, the more dexterous it becomes. This objective function can be tailored to support a combination of competing performance criteria such as obstacle avoidance, mechanical advantage, minimization of joint velocities, end of joint travel avoidance, and conservative pose control.

R2 Singularity Negotiation Algorithm

The most powerful feature of the R2 inverse solver is its ability to recognize kinematic singularities. The inverse solver masks motion commands, which are not physically realizable due to a singular configuration. For example, in an extreme singular pose of a seven degree-of-freedom arm, it may degenerate into the kinematic equivalent of a five degree-of-freedom arm, and therefore a particular commanded direction or rotational direction could not be achieved. The inverse solver detects this condition and remedies it by removing the unattainable direction constraint from the list of six constraint equations. The robot utilizes the seven joints to achieve the remaining five attainable directions. The robot arm, in this instance, has two degrees of redundancy to satisfy the five valid constraint equations and minimize the objective function. In a sense, a singularity is a special case of redundancy and, in the context of the R2 inverse solver, redundancy is always a singular condition.

Tool Contact Control

The R2 Control provides two types of tool force strategies; impedance and compliance control. Both techniques cause the tool to mimic a spring-mass-damper system in each of its six degrees of freedom. Also, each technique compensates for the gravitational forces of the tool and payload. Robotic applications such as general assembly, deburring, polishing and grinding, which are performed at high speeds with accompanying large transient forces, must employ impedance control. Impedance control provides the high bandwidth force response required to maintain stable tool contact with a rigid environment. Impedance control relies on the servo controller commanding torque to each joint. Consequently, only manipulators equipped with direct drives or joint based torque sensing are candidates for impedance control.

Compliance control is appropriate for low gain, low bandwidth applications, where the stability criteria are less demanding but more accurate force measurements are required. A sensor mounted at the tool plate measures the six DOF contact forces. The calculations for the mass and the principle axes of inertia are based on the tool/payload definition and the apparent mass and inertia of the robot arm.

Trajectory Planner

The R2 trajectory planner provides two types of trajectory planning: coordinated Cartesian tool control and joint space motion. Coordinated tool control produces linear and circular tool motion of a specified tool point from the current position to a six-degree of freedom target position. The trajectory planner can be readily extended to support a non-rational B spline basis. At the start of each cycle, the entire trajectory is recalculated unconditionally based on the state of the system and the present command. This approach facilitates real-time sensor guidance. The trajectory planner accepts three sets of velocities, linear, orientation and self-motion, with each set having an intermediate and final velocity. In addition, a new path and target tool position can be dictated every control cycle.

Upper Layer

The upper level of the R2 Control provides a very efficient lead through capability to teach, verify and modify a program. All the operator commands are available at the console as well as at the pendant. All taught moves can be 'stepped' in a forward or reverse direction. Moves and routines (i.e. paths) are easily created, inserted, modified and deleted. Mathematical and logical operator functions can be utilized for conditional branching and nested subroutine calls. The taught programs are saved as text files, which provide a means for self-documentation.

R2 API

The R2 Control Software™ supports a robust application programming interface (API) set to permit third party integration. All the real-time controller commands are supported in its API so that the manipulator can be directed from either a separate system remotely via a communication link or an inter-process communication protocol. This API de-couples the higher-level control development from the lower level motion controller.

Welding Features

The R2 Control provides advanced welding capabilities. It supports adaptive welding in the areas of cross seam and stickout tracking and variable fill of non-uniform cross sections. The R2 Control is able to perform welding on ten multipass segments in a completely arbitrary order. The tool roll constraint can be designated a "don't care condition", which provides another degree of redundancy to the manipulator. Spatial coordination between the manipulator and an arbitrarily defined positioner is supported.

R2 Configurable Hardware Architecture

The versatility of the TCP/IP standard and INtime's NTX communication protocol permits tremendous flexibility with respect to configuring the R2 control hardware. The entire R2 Control including the SolidWorks simulator can execute on a single PC system. On the other hand, each of the Window client processes and the INtime real time component can execute on its own separate PC system without any changes with respect to the code. In a typical configuration, the R2 Server and the INtime component share the same CPU, while the R2 Master, the R2 SolidWorks simulator and possibly a third party specialized client share the same PC system.

The R2 Control has configurable I/O capabilities. Only a text file modification is required to configure the controller hardware to process the specified feedback devices, amplifiers, etc.

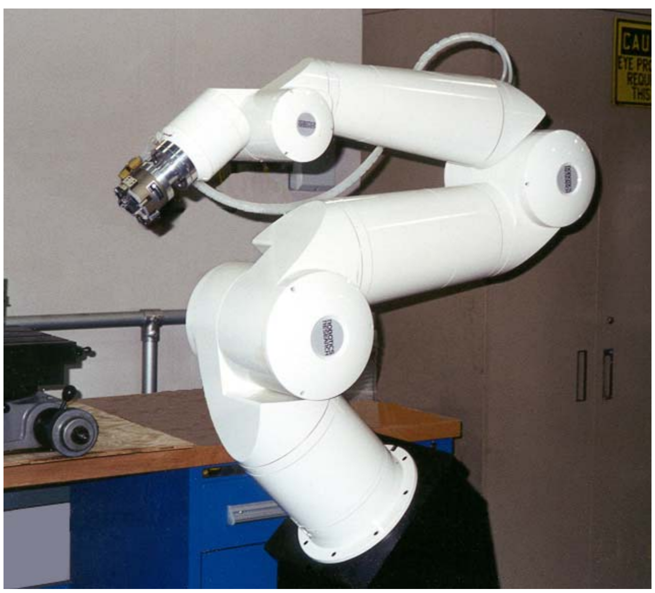
Custom Applications

In parallel with its manufacturing operations, Robotics Research has worked under contract with industrial customers and government agencies to adapt its proprietary mechanical design and control technology to new applications. For instance, the company served as principal subcontractor to Grumman Aerospace Corporation for the manipulator design and control algorithms in the NASA Flight Telerobotic Servicer program and produced the first 17 DOF manipulator operating under coordinated control.

◄ Also, for NASA Goddard Space Flight Center, RRC developed a flight-qualified, seven degree-of-freedom manipulator for HST-SAT, the Hubble Telescope Servicing program.

Under contract with Oak Ridge National Laboratories Y-12 plant, the company produced a seven degree-of-freedom, modular manipulator for a glovebox operation of a saltless direct oxide reduction process.

And, in conjunction with Ford Motor's Advanced Manufacturing Technology Development group, the company demonstrated the assembly of complex gear trains and clutch disks using its manipulator products and joint torque based impedance control algorithms, representing a significant breakthrough in automated assembly capability. This algorithm allows the operator to specify stiffness and damping at the robot's tool in all six degrees of freedom, in addition to any redundant degrees of freedom.



The algorithm continuously commands robot joint torques required to achieve tool forces based on the current position of the tool, the desired position of the tool, and the specified stiffness and damping in each Cartesian direction. With this high bandwidth control, excessive forces do not occur and the capability for accurate positioning is retained. The RRC system is the first system to successfully demonstrate this capability.

RRC has also applied the R2 Control Software™ to other manufacturer's robot systems. In 1999, RRC installed its control software on an arc-welding robotic system for Caterpillar, Inc. The robot, which has been produced by Cybo Robots for many years, was at that time the largest arc welding system ever constructed. The welding cell consists of a six degree-of-freedom arm mounted on an 8m linear traverse and a two degree-of-freedom work holding positioner. The R2 Control Software™ provides simultaneous, real-time Cartesian coordination of all nine axes, spatial coordination of the manipulator with the positioner, robust kinematic redundancy resolution and adaptive welding. Weld quality has been significantly improved and production time greatly reduced. The user interface and scheduler facilitate efficient and intuitive lead through, online and offline programming. The inverse kinematic redundancy control algorithm virtually eliminates the problems of singularities and increases the dexterity of the arm. The R2 control is very configurable and portable. It will support any type of kinematic configuration and can be implemented on any commercial real time operating system.

RRC is currently under contract with the US Department of Defense, US Army, to implement the universal R2 Control for automating military material handling equipment and unmanned ground systems in unstructured environments. The architecture and control methods are designed to control any manipulator on any mobile platform, independent of their individual capabilities.

The control system developed in this program will not only increase the application of robotic systems but is targeted to provide automatic and shared control of existing manually operated equipment. Practical military and commercial applications include material handling and assembly, missile loading, rearming tanks, construction, vehicle refueling, explosive ordnance disposal/mine clearing, cleaning, sand/bead/water blasting and painting/coating.

The R2 Control has been integrated into an existing hydraulic crane mounted on a military vehicle for munitions handling. The system consists of an array of sensors and an operator control station within the cab of the vehicle. It relies on world modeling, sensory feedback, force control, redundancy control, and an advanced shared control operator interface.

Smart Crane Ammunition Transfer System

Applying this technology to the US Army platform significantly reduces cycle time and minimizes personnel requirements for the manipulation of military payloads in unstructured environments. In addition, the R2 Control is affordably adaptable to many existing hardware systems for implementation in a wide array of applications in both the government and commercial sectors. By retrofitting existing manual systems, the expense of developing new, task specific hardware is eliminated.

Summary

The strength of the company's technology enables it to be readily applied to a broad range of applications throughout a diverse spectrum of industries without significant re-engineering. From industrial use to space flight operations, this technology provides the flexibility demanded for cost effective application of automation.

The integration of the company's redundant kinematics algorithms and trajectory planning methods represent the most powerful approach yet demonstrated for controlling redundant linkages, providing reliable, efficient coordinated control of robot systems with any number of joints and arms operating in an 'intelligent' (i.e., reflexive), sensor-driven mode.

Robotics Research Corporation has been awarded nine patents representing a highly integrated body of technology. The mechanism design and motion control patents, in combination with the torque-loop servo-control scheme, effectively protect RRC's basic designs for configurable manipulators employing joint-mounted actuators.

RRC's staff possesses world-class expertise in each key facet of robotics technology — control mathematics, software development, digital and analog electronics engineering, and mechanical design and analysis.

RRC customers include Ford Motor Company's Advanced Manufacturing Technology Development center, NASA's JSC, JPL, GSFC, Langley Research and Ames Research Centers, the National Institute of Standards and Technology (NIST), Space Systems Loral, Northrop Grumman Aerospace, Lockheed Martin Palo Alto Research Laboratories, McDonnell Douglas Space Systems, North American Philips, US Department of Energy's Oak Ridge National Laboratory (X-10 facility and the Y-12 Plant), Los Alamos National Laboratory, the US Department of Defense's Army Armament Research, Development and Engineering Center, Caterpillar, Inc. and several universities in the U.S., as well as Advanced Robotics Research Ltd. and British Nuclear Fuels Ltd. in the U.K., NASDA and the NEC Mechatronics Lab in Japan.

Since the company's inception in 1983, RRC has been dedicated to delivering products that meet industry's demand for innovative, cost-effective automation solutions.

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