Chapter 1

THE NEW ROBOTIC ERA

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With tremendous advances in computer communication technology, computerized robots connected to networks can be efficiently used in the design of intelligent telerobots. Intelligent telerobots allow remote operations by using a control workstation that is connected to a robotic workstation through a computer network. Fast networks allow intensive information exchange between the two workstations. Providing high quality visual and sensual information in a telerobotic system will enable sophisticated remote operations with a feeling of excellent connectivity. The aim is to develop an intelligent and networked robotic system in which the workstations exchange reflected-force feedback and stereo-vision information. A new multimedia robotic system will be designed in the next decade for supporting a class of telerobotic services allowing humans to remotely extend their manipulative capabilities and skills over a computer network. In this context, research will address the network interface for the master and the slave workstations, the implementation of the network connectivity and transfer of control, the force feedback, and visual information, and the handling of the delay problem. Intelligent robotics has a number of critical applications in remote surgery operations emergency cases, tight safety conditions, and hostile environments. Currently developed multimedia communication and services can be efficiently used to provide specific telerobotics services. The wide spread of these communication services in the future computer communication will provide the needed backbone for the implementation and wide spread of telerobotics.

1.1 Historical development and future of robotics

The use of remotely-controlled manipulators appeared during the second world war (1939-1945). These robot arms were used in loading and manipulating radioactive material. A remotely-controlled manipulator consists of a master arm interconnected to a slave arm such the motion of the slave arm is a replica of the master arm motion. The master arm terminate with handle that is operated by a human operator. Thus the motion of the operator arm is dictated to the slave arm. At that time the interconnection was entirely mechanical (steel cable, wire, and ribbon) and therefore the distance between the master and slave stations was limited to a few meters.

In 1950 a company (General Electric GE) implemented a remotely-controlled manipulator by using an electrical interconnection and DC motors to regenerate the torque that was previously transmitted through the cable. They also used simple visual feedbacks (video). As a result the distance between the master and the slave stations could be made arbitrary.

In the period from 1950 to 1960 a number of companies like Unimation (Westinghouse) developed computer-controlled robot systems. The idea is to extend the concept of computer programming to robot task programming so that a program can associated to a given robot task. Thus by repeating the execution of the program the task could be repeatedly executed. This allows reproducing a task trajectory (welding, painting, etc.) based on recording a few trajectory points in the computer memory and the use of a program to regenerate complete trajectory. This allowed programming of tasks like painting, welding, part handling, and many other repetitive tasks. However, no sensing was provided and the robot could not tolerate any kind of errors (friction) during its operations. This category relies on position accuracy which is expensive to achieve in a mechanical system. Therefore the need for sensing the environment and the adoption of a new style of programming (closed loop) to provide robot task robustness and adaptation versus all kinds of uncertainties and noise.

The period from 1960 and up was marked by many research efforts aimed at developing robotic sensors. For example the simple contact sensor, proximity sensor, ultra-sonic sensor, tactile (haptic) sensor, force sensor, and the more complex machine perception and vision. In this period the foundation of the motion coordination of kinematic chains were developed based on the Geometrical and Jacobian methods. Also the robot dynamics received lot of attention. For example the *Lagrange Formulation* and the *Euler Formulation* of the dynamics of mechanical chains.

The period from 1970 to 1980 was marked by the development of robotic software such as the use of LISP for assembly operations. Here simple vision systems were interfaced and used within a single robot programming language in the design of simple tasks. As application automatic stacking of blocks with some strategy was developed (Stanford University). Another application is the tracking of moving object on an assembly line (Cincinaty Co.). At Purdue a simple water pumps was assembled by a robot arm. In France, Renault developed a vision system to recognize unstructured objects and their grasping by a robot arm. At the Drapper Labs a force sensor could provide some passive and active robot compliance, a very useful task to avoid jamming in assembly operations.

The period from 1980 to 1990 was the development of many robot programming languages such as VAL (Unimate), AL (Univ. of Stanford), Pointy (Polytecnico di Milano), Autopass (IBM), LAMA (INRIA-France), etc. The robot kinematics, the Jacobian method, and robot dynamics received lot of attention as well as the parallelization of the inverse robot kinematics and robot dynamics. There has been a deliberate effort to the computational requirement of robotic systems as well as the parallelization of the inverse robot kinematics and robot dynamics over a set of parallel communicating processors.

The period from 1990 to 2000 was the development of many dedicated parallel computer architectures (MIMD) suitable for the control of high-performance robot systems, i.e. computing of robot kinematics and robot dynamics on-line. Macro-pipelining and systolic arrays were proposed for similar real-time tasks. The method of parallel processing and task scheduling were largely used for statically scheduling the robot computational tasks. At the programming level, database development for object modeling were investigated and proposed. Collision avoidance between the robot and its environment and objects were largely studied and many algorithms proposed. Telerobotics was used in space exploration as well as in servicing and maintaining space stations. Micro-robots were also used in heart surgery after association with stereo vision. A number of such robotized surgical operations proved that robotics has a lot of potential in the operating room. Networked telerobotics will benefit from the international computer network which provides the needed connectivity between the operator station and the robot station. Moreover multimedia 3-D visualization will be the complementary technologies needed for telerobotics to provide a real network extension of human manipulative capabilities.

The genealogy of robotics can be summarized as follows:

- Post World War II: Teleoperator systems for dangerous materials, prosthetic devices.
- Early 60's: Digital logic makes computer control of machines feasible.
- Late 60's: Space program advances intelligent, computer controlled systems. Microprocessors embedded in systems.
- 70's: Artificial Intelligence adds "smarts" to robots. Robotics begins to become both hardware and software intelligence.
- 80's: Computer Controlled Sensors become a main component of (robotic systems. Vision sensors, robotic hands, tactile sensors, 3-D sensors. Systems include many connected sensors and processors.
- 90's: Proliferation of application systems, including factory automation, virtual reality, teleoperator systems, medical devices, intelligent vehicles, space probes.

Robotics has the following features:

- Capability: space, undersea, hazardous areas, medicine, and manufacturing.
- Flexibility: greater productivity, better quality control
- Human values: allows workers to concentrate on more interesting jobs instead of boring repetitive jobs. Remove workers from unsafe jobs. Creates more leisure time.
- Natural extension of building more intelligent machines. As robots become more capable, range of applications increases.
- It's fun! Get machines to cut the lawn, take out the garbage, do the wash and ironing, vacuum the room...

However, robotics has the following drawbacks if it not utilized in right way:

- Dehumanizing, unemployment, job displacement.
- Science Fiction scenarios. Robots controlling the world, out of control machines inflicting harm and damage, humans becoming an inferior species...

At the present day robotics is characterized by the following features:

- Robots are still not as capable as humans...
- Robots still cannot perceive arbitrary environments.
- Robots need things to be in right place at the right time.
- Extensive use of fixtures, constrained environments.

- Special purpose grippers, tooling needed. Hands not yet fully dexterous.
- Vision systems limited. Controlled lighting. Part location and orientation known.
- Poor error recovery if things don't go well...error leads to failure.

To advance robotics we need to solve the following set of open problems:

- Sensors are relatively crude.
- Noise still a problem.
- Processing is still sequential, not parallel.
- Real-time response difficult to achieve.
- Models have difficulty representing full 3-D complexity of the environment.
- A robotic system is a distributed set of heterogeneous processors with tight scheduling constraints, and a low bandwidth communication system. This is a poorly understood domain.

The main direction of robotics research are the following:

- Building better robots: reliability, high speed, programmability, low cost.
- Manipulators: real-time control, multiple arms, force and position control, redundant degrees of freedom, flexible materials for arms, Mobile manipulation.
- Sensors: More accurate, error free sensing systems. Integrating sensors with intelligent action. Higher resolution cameras, more dexterous hands, accurate force sensing.
- Standardized, portable languages and user interfaces.
- Architectures: Fast, multi-processor, concurrent environments. Tools for real-time debugging and error recovery.
- Modeling: Building models that efficiently and accurately model geometric, topological and functional attributes of 3-D objects. Integrating models with sensors.
- Task Level Planning: task level plans and decompositions of those plans. Recognizing error states. Obstacle and collision avoidance. Navigation and autonomous behavior.

1.2 Structure of a robot

A robot arm is a flexible mechanical system [12, 45] that can be programmed by a computer to carry out manipulative tasks by means of repetitive motion-sensing steps. Mechanically, a robot arm consists of a chain of links the are interconnected by active joints [32, 49, 2].

A joint can be either revolute or prismatic as shown in Figure 1-a and -b. The first end of the chain is the robot base and the second end is equipped with a gripper or a tool and used to operate the object. A robot arm made of revolute joints is shown on Figure 1-c. Robotics has also applications in a wide domain of applications ranging from Industrial manufacturing systems, hostile environment including undersea and space applications, and medical applications.

Robotics is traditionally used in a large class of repetitive industrial tasks such as welding, spray painting, and loading/unloading of equipment. Industrial Robots are widely used in integrated manufacturing systems which is a highly computerized environment that allow programming and scheduling the operations of multiple production machines and robots in a highly cooperative manner. The objective is to increase the degree of automation, production throughput, and provide flexible means to change the attribute of the product without necessarily changing the machines.

Applications in hostile environment range from the manipulation of hazardous material to space and undersea utilization of robots. Hazardous material can be radio-active, dangerous chemical and biological materials which require the use of a pair of interconnected robot arms called master-slave tele-operator.

Essentially the motion of the slave is a replica of the master motion in a master-slave robotic system [24, 11, 34]. The master arm is operated by a human operator placed in a safe place, while the slave arm operates directly in the hostile environment. Current research issues in tele-operation address the problem of improving the quality of the interface between the two arms which depends on the extent of information exchanged between the two arms. A sophisticated tele-operator allows exchanging force "feeling" and visual information which are sensed within the slave environment and forwarded to the human operator through the master arms. Another important factor is robot power-steering which allows controlling the mechanical impedance of both master and slave arms.

Medical applications range from the use of robots to replace a missing upper or lower member for the patient to the use of robots as sophisticated tools in performing surgical operations that require the highest accuracy and controllability.

1.2.1 The motion coordination concept

Motion coordination of robot arms deals with the problem of orchestrating the motion of all the joints in order for the robot hand to follow a prescribed trajectory [62, 63, 64]. Implementing a motion coordination system requires analysis of the geometrical interconnection of the robot links for finding closed form Kinematic relations between the robot hand position and orientation and the joint variables. Fundamentally, two approaches [64] are used: 1) the Geometric model, and 2) the Variational model. Figure 1-c shows the definition of robot geometric variables and hand frame of reference in the case of a fully revolute robot arm. The geometric variables are located at the link joints and used to move the links by using motors. The design of optimized coordinate transformations has been proposed for many robot arms. Each approach includes numerical kinematic analysis [57] of general robotic manipulators together with treatment of singular points and the selection of suitable solution.

In the Geometric model the robot hand is represented by an effector vector which specifies the robot hand frame position and orientation [2, 1]. The topological features of the arm allows finding the geometric model as set of non-linear equations where the unknown variables refer to the robot degrees of freedom. This system equations allows finding the position and orientation of the robot hand that corresponds to a given joint vector. The motion coordination problem is just the inverse problem. One needs to find the joint vector that can be assigned to the robot arm through the control system in order for the robot hand to satisfies some position and orientation. This problem arises in real-time control of robot arms which means that each point of the robot trajectory requires solving the inverse geometric system.

Mainly, the inverse geometric problem consists of solving a system of 6 non-linear equations for finding the value of joint vector. Generally, there are two problems for finding a solution

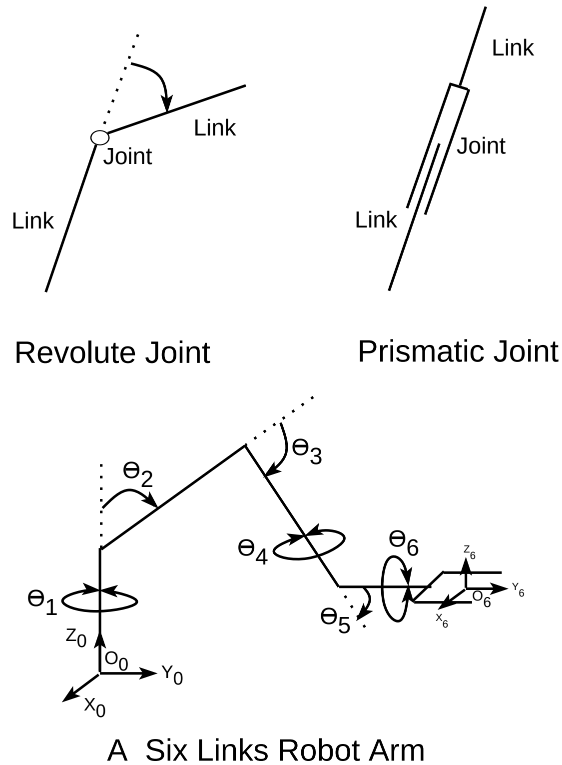


Figure 1.1: General schematic of a robot arm

out of the inverse geometric model: 1) multiple solutions, and 2) singular arm configurations.

Generally, multiple but finite number of solutions are obtained even in the case where the robot arm has 6 degrees of freedom together with 6 non-linear equations that corresponds the the robot hand position and orientation. Generally, the selection of one solution out of a few solutions requires additional information such as motion continuity or minimum incremental motion. Motion continuity criteria leads to select the solution that is closer to previous trajectory points according to some distance.

The problem of robot singularity arises when the above system equation admits infinite number of solutions. This means that for some singular arm configurations the knowledge of the robot hand position and orientation is not sufficient for finding all the robot angles. Some heuristics can then be used to assign values to the degrees of freedom that cannot be identified directly the above system equations. Figure 2 shows the case of multiple solution, singular solution, and redundant manipulator that have greater accessibility but with larger number of possible solutions and singularities.

It is known that 6 degrees of freedom are required to find a unique position and orientation for any object in the three dimensional space. The inverse geometric model faces a problem in the case of redundant robot arm for which the dimension of the joint vector is more than 6. In this case, different methods can be used to constrain a subset of components of the joint vector such as finding a solution with least displacement.

The structure of a motion coordination system based on the inverse geometric model is shown in the Figure 3-a. The input trajectory of the robot hand is the effector vector denoted by $E_d(t)$ for which the inverse geometric system $G^{-1}(E_d(t))$ provides a solution $\theta_d(t)$ which in turn applied to the robot controller. The robot effector represents the position and orientation of the robot hand or the manipulated tool. The robot controller shown in the figure is a simple proportional-and-derivative controller that operates on the position

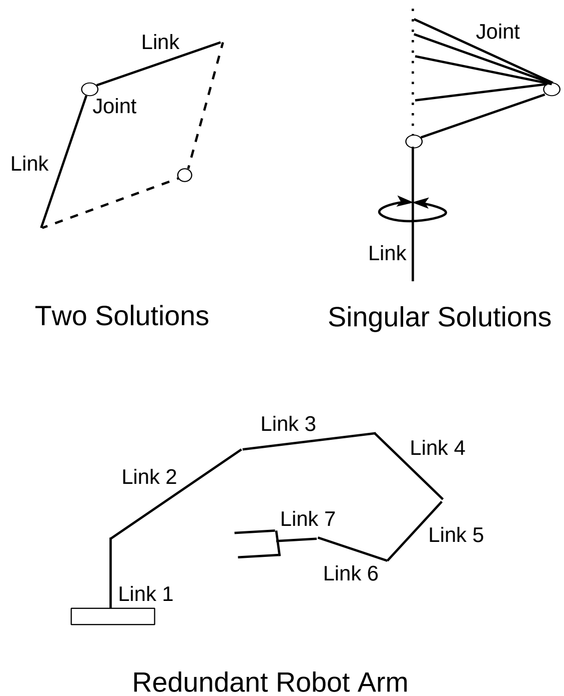


Figure 1.2: Multiple solutions, singular solution, and redundant arms

error $\epsilon = \theta_d(t) - \theta_r(t)$, where $\theta_r(t)$ is the current robot configuration. The position error ϵ is transformed to a corrective torque by using power amplifiers and applied to each link actuator. for low speeds, the behavior of the closed loop can be modeled by using a set of second order linear differential equations. Increasing the arm speed leads the robot trajectory to deviate significantly from the prescribed trajectory which indicates the need to consider the robot dynamics as an integral part of the robot controller. Therefore, the use of the robot arm dynamics is one pre-requisite to alleviate the above problem in the case of high speed motion. Figure 3-c shows the robot dynamic controller according to Lagrange formulation which consists of evaluating the external forces to which each link is subject to [2, 1]. These forces are: 1) the inertial coupling, 3) the coriolis effect (cross angular velocity effect), 3) the centrifugal effects (square angular velocity effect), and 4) the gravity effects. The principle of the controller shown in the figure is to compensate for all these external forces after computing their values on-line by a dedicated computer. The dynamic controller eliminates the effect of external forces by generating opposing motor forces. The Newton-Euler formulation of robot dynamics [49, 12] is a much more efficient formulation than the Lagrange formulation in terms of the number of arithmetic operations needed to compute the dynamic joint torques.

1.2.2 The variational model

The geometric model provides some correspondence between the robot hand position and orientation and the robot joint vector. The variational model relates variation in the hand vector to variation in the joint vector. Assume the current hand vector is $E_0 = G(\theta_0)$, the problem is to find the increment $\Delta\theta$ that satisfies $E_0 + \Delta E = G(\theta_0 + \Delta\theta)$. For this one is to differentiate the system $E = G(\theta)$ which gives $\Delta E = J(\theta)\Delta\theta)$ for small increments ΔE and $\Delta\theta$), where $J(\theta)$ is the matrix of partial derivatives or Jacobian associated to $E = G(\theta)$.

Implementing a motion coordination system by using the variational approach consists of finding the increment $\Delta\theta$ that corresponds to a desired increment ΔE of the hand vector. In

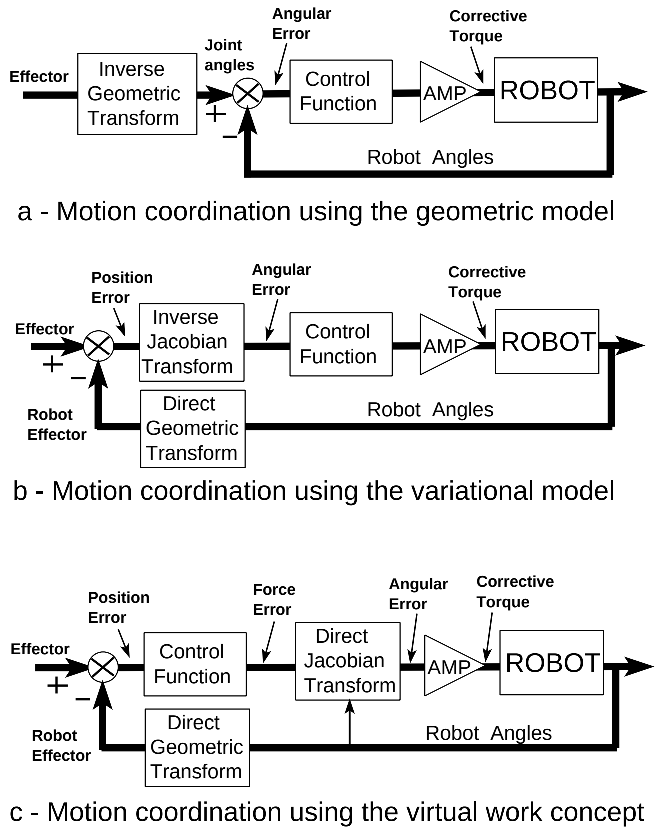


Figure 1.3: Methods of robot motion coordination

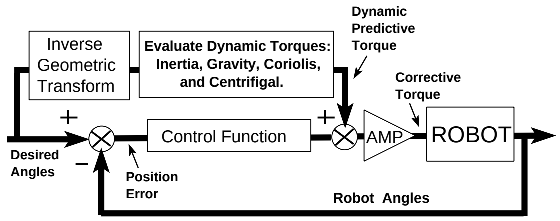
other words we need to solve the linear system $\Delta\theta = J^{-1}(\theta)\Delta E)$ which requires a two-steps approach: 1) evaluating $J(\theta)$ for the current robot vector θ), and 2) finding the inverse $J^{-1}(\theta)$. In the following we present a short analysis of the problem.

The matrix $J(\theta)$ is a square $n \times n$ matrix whenever $dim(\theta) = dim(E) = n$. Therefore, finding $J^{-1}(\theta)$ is conditioned by the non-singularity of the determinant $(det(J(\theta)) \neq 0)$. Matrix $J(\theta)$ is singular whenever the arm configuration satisfies either of the following conditions is satisfied: 1) two or more components of the joint vector are co-linear, or 2) the value of one joint component or more is such that the motion of hand frame is constrained at least in one direction. Solving for $J^{-1}(\theta)$ under the above conditions can be done by finding the $\Delta\theta)$ that corresponds to an increment ΔE which is the closest to the desired one.

The matrix $J(\theta)$ is a rectangular $n \times m$ matrix if $dim(\theta) = m$ and $dim(E) = n$. This corresponds to the case of redundant arms where $m > n$. In this case, infinite number of solutions $\Delta\theta$ exists and each satisfies $\Delta E = J(\theta)\Delta\theta)$.

Solving $\Delta E = J(\theta)\Delta\theta)$ requires finding a generalized inverse $(A(\theta))$ that satisfies either conditions: $J(\theta)A(\theta)J(\theta) = J(\theta)$ or $A(\theta)J(\theta)A(\theta) = A(\theta)$. An infinite number of generalized inverses can be found. One interesting generalized inverse is the pseudo-inverse (A^+) that minimizes the sum of increments of the joint vector, i.e. minimizing the quadratic function $Q = \Sigma_{i=1}^{m}(\Delta\theta_i)^2$. The pseudo-inverse is unique and satisfies $JA^+J = J$, $A^+JA^+ = A^+$, $(A^+J)^t = A^+J$, and $(JA^+)^t = JA^+$.

Implementing motion coordination based on the variational model is shown in Figure 3 in which the difference between the desired effector vector and the robot effector vector represent the effector error. The effector error is converted into robot joint angle error by using the inverse Jacobian of the robot arm. The correction loop occurs at the hand vector $E_d(t)$ level.



b - Dynamic control by using Lagrange formulation

Figure 1.4: Lagrange scheme for robot dynamics

The error $\epsilon_E = E_d(t) - E_r(t)$ where $E_r(t) = G(\theta_r)$ is the current robot hand vector. The hand error ϵ_E is converted to an error ϵ_θ by using the inverse Jacobian matrix of the arm $J^{-1}(\theta)$. The error ϵ_θ applied to the control function whose output determine the corrective force and torque to each joint component. The control function can be a simple proportional and derivative action [49, 45, 2, 1] whose parameters can be dynamically adjusted depending on dynamic configuration of the robot. This approach allowed maintaining constant closed-loop performance of overall robot system.

A high quality robot controller must accounts for the robot dynamics in addition to motion coordination. Two schemes for robot dynamics are shown on Figure 4, where the first scheme is based on calculation of Torques according to the Lagrange Model of robot dynamics and the second is based on the Newton-Euler robot dynamics which is more efficient approach because the number of arithmetic operations it requires in one iteration is much than that needed in the Lagrangian operator.

1.2.3 The control, planning, and robot cooperation

Generally the kinematic control [64, 55, 4] is integrated with dynamic control [49, 32, 12] which allows some regularity in the computation of next robot control parameters. A recursive formulation of kinematic and dynamic equations for robot arms have been proposed in [61] which contribute in promoting the regularity and modularity of robot computations.

Another important aspect is the architecture of the robot arm and the definition of its degree-of-freedom (d.o.f.) and their number. Redundant robot arms have more than the minimum required (six d.o.f.) for positioning and orienting an object in the 3-D space. The benefit is increasing flexibility and accessibility into complex structures. However, the motion coordination system becomes more complex [7] and requires extra-constraints in order to find unique space solution.

Robot arms must be able to cooperate in achieving tasks in a flexible manufacturing industry. More over, robot arm must be capable of interacting such as passing tools or working on the same piece. Multiple robot interaction leads require taking into account the cooperative motion control aspects in designing the robot controller. Cooperative motion control of multi-robot arms [6, 27] was extensively studied during the past ten years.

Trajectory planning is an important step task automation and proved to be very useful in an robot assembly operations. Trajectory planning requires some knowledge of the environment in order to avoid collisions between the robot arm and the objects available in its work space. Planning the robot path in the presence of obstacles has been studied in [22] on the basis of evaluating a distance function separating scene objects from robot arm. Due to large computational load, optimization of path planning [23] on the basis of a sequential search strategy which allowed faster collision avoidance than previous proposals. To optimize further the path planning computation an approach based on decomposing the trajectory into path and velocity modules was proposed in [30]. In [30] the trajectory is decomposed into three modules which are path, velocity, and splines. The use of splines allowed the generation of smooth collision-free trajectories. While the computational complexity is increasing with increasing sophistication of the robotics modules, multiprocessors were proposed [3] to parallelize robot computations in order to maintain high enough interaction rate between the robot and its workspace. Parallel processing is needed to parallelize robotics algorithms which enables increasing the level of robot intelligence through increasing algorithmic sophistication without degrading response time.

While robot cooperation is needed for sharing the work eye-hand coordination is becoming critical resource become it allows the robot to "see" its workspace and to modify the state of its work space based on visual information. Visual information are heavily used by human which can achieve very sophisticated tasks by combining intelligence with visual and force sensing. For robotics the objective is to develop robotics ability to automate tracking and grasping of moving object on the basis of hand-eye systems [5, 43]. Analysis of force feedback and force sensing is proposed in [46] which suggest a programmed compliance for error corrective assembly. In some cases force sensors were designed at the robot gripper level [1] to allow direct measurement of external forces that influence the manipulated object. Force information can be efficiently used in force regulation in order to generate corrective robot position which avoids jamming situations in assembly operations.

1.2.4 The role of force feedback in robotics

In traditional master-slave systems the operator applies intentional forces and utilize sensory feedback such as visual display and reflected force on the master arm for evaluating the current control state against his intention. Therefore, the performance of the master-slave system depends on how the operator perceive sensory information precisely and in generating controls in a timely fashion consistent with his perception and intention.

There are objective that must be achieved in a high fidelity master-slave system which are: 1) proper man-machine coordination through sensory feedback, 2) robust execution under operator's control errors and time delays, and 3) automatic execution of functions that are handled with difficulty by the operator.

While interaction between parts may be visualized using vision system, the most reliable method of sensing physical contact and controlling relative motion of contacting objects is through force sensing and control. The contact often involves close tolerance where the resolution of a vision system is insufficient to guide the relative motion and orientation. Force sensing provide the needed information especially when the force measurement is located as closely as possible to the slave robot hand. The response to sensed or measured forces may often be achieved through passive or active compliance. In all cases, compliance causes a corrective motion of the slave arm hand which tends to decrease the applied forces which has the effect of avoiding jamming and excessive friction.

Much effort has been extended in achieving improved man-machine coordination through force feedback [35]. Several attempts have been made to develop an analytical model to teleoperator control system such as the two-port network model [24] and [65] of master-slave systems. The use of robustness in the design issues were addressed in [31] and the incorporation of operator's dynamic in the control loop was studied [35]. Matching the mechanical impedance in bilateral teleoperated systems was studied in [47, 48]. Shared compliance control has been introduced to compensate for the imprecision and the low bandwidth of operator sensory-motor coordination when dealing with compliance forces. This has lead to the development of a new generation of master-slave systems where the machine plays a role of an active partner as it provides the human operator some cooperative perception, decision-making, and local task execution.

The time delay in man-machine interface may seriously degrade the fidelity of master-slave systems and may cause control instability [60]. The issue of integrating large time delays in space master-slave systems were proposed through teleprogramming [21] and tele-sensor programming facilities [14] In tele-sensor programming facilities the stability of the master-slave is maintained in real-time by controlling of the force and position coupling signals between master and remote slave robots. This method does not requires accurate simulation but suffer from performance degradation in the case of large delays.

In teleprogramming the operator teleprogram the remote slave or sensors by executing tasks in a simulated delay-free environment in local master while interacting the remote slave through clutches [11]. This method seems to be more robust provided that the modeled system is accurate and remote slave is capable of automatically correcting errors incurred by any inaccuracies in the simulation.

The operator dynamics in control generation must be incorporated in the control loop of master-slave systems. A controller without without operator dynamics in control loop may be in flaw. In [36] an operator dynamic model that reacts to both visual and force feedback is incorporated in the controller design. The stability and transparency of master-slave systems in the presence of communication delays are studied in [34]. The control system should be robust to human control errors which requires optimizing the controller with human dynamics in the control loop as the prerequisite for supporting operator's comfort and ease of operations.

The goal of telerobotics is to provide the operator with the actual feeling of what is going on at the slave, possibly with size and power scaling, so that the operator can generate appropriate control to slave. The introduction of shared control and the presence of time delays in between the local master and remote slave, the original goal of telerobotics has become difficult to achieve. For example under shared position and compliance control such as a direct reflection of sensed force to the operator. In this case the operator tends to continuously extend the position errors because of the operator realize that automatic compliance control is compensating for the position errors. This uncertainty of the operator in evaluating the position errors may significantly degrade performance of shared compliance systems. Telemonitoring was proposed to provide the operator with an intuitive and natural feeling of how the remote slave behaves through monitoring of the position and force errors. When the slave is unable to follow a control due to environmental constraints or due to delays the position error force feedback is increased so as to resist the motion which allows warning the operator through increased force reflection.

The design of high fidelity telerobotics systems requires monitoring of the force feedback and and incorporation of operator's dynamics in the loop in order to achieve robust control under shared control and time delays. The response of the operator to visual and force feedback must be modeled and taken into account by the controller. This involves active modification of master and slave arms' dynamics of generalized impedance control and global system optimization. A new perspective on the design of advanced telerobotics systems must necessarily incorporate visual and force stimuli into the control loop.

1.2.5 The role of vision in robotics

In robotics researchers seek to transform the recordings of real events and environments into digital scenes that remote users could interactively view from any desired perspective. This growing technology promises enormous rewards in such applications as remote control, remote surgery, teleconferencing, robotic and industrial computer servomechanisms. Intelligent robotics (IR) integrates video and real-time interactive graphics, a marriage of well-developed, dynamic technologies that will give IR great utility as a communications medium. Like video, new information in this medium arrives at every frame during the presentation. In contrast to conventional algorithm intensive, model-based graphics, we can characterize IR as a data-intensive medium. Robotics and Virtual Reality (VR) have much in common but differ in their emphasis on reality [51]. VR depicts artificial creations transformed to look and feel real. Robotics on the other hand, transforms reality to enable interactive viewing. In this respect, robotics is to VR as a movie is to an animation. While the latter is created entirely by an artist the former captures life and all its dynamics, staged or real.

The problem of virtual view creation, or view synthesis or interpolation of real scenes, has received increasing attention in recent years. Current approaches divide into two classes: image-based and model-based. Image-domain methods employ warping techniques to interpolate intermediate views from real images. Model-based methods first recover the geometry of the real scene; the resulting 3D model can then be rendered from desired viewpoints. In [41, 17] the authors used computer vision and computer graphics methods to generate full-3D video version from 2D video recordings. Hirose in [26] described the spectrum of methods used to generate reality-based virtual worlds and brings out some major differences between interactive computer graphics and IR.

For the image-based methods, the best-known image-domain method is Apple's QuickTime VR .2 consists of capturing the 360 degree views (cylindrical panoramic images) of an environment from a fixed position, you can interactively adjust view orientation by rendering the corresponding portion of the panorama [38] Other approaches use image warping. Chen and Williams [9, 10] determined camera transformations with pixel correspondences, then used morphing to generate intermediate views. Skerjanc and Liu [54] used known camera positions to obtain depth information and generate virtual views. Chang and Zakhorl [8] obtained depth information by using an un-calibrated camera that "scans" a stationary scene and transforms points on camera image planes onto the plane of the virtual view. In [50] Seitz and Dyer proposed exploiting monotonicity along epipolar lines to compose physically valid intermediate views without the need for full correspondence information. Several recent developments employ the plenoptic function, which describes light rays visible at any point in space. McMillan and Bishop [40] developed an image-based rendering system using a 5D representation and cylindrical projections. Levoy and Hanrahan [37] used 4D formulations of the plenoptic function for virtual view synthesis. In general, image-domain approaches need fewer computational resources than 3D model-based approaches, but they often limit supported virtual views to a narrow range.

At a high level, a model-based approach to 3D digital video creation involves three processes. First, an event or a scene must be recorded by multiple strategically located cameras. Moezzi et al [17] used 17 cameras surrounding a stage area to record various performances. In a similar way Kanade et al. [29] used six to eight cameras, placed around a hemispherical dome five meters in diameter, to record an actor in motion. Fuchs et al. [20] used image data acquired by many cameras installed around a small environment such as a conference room. By contrast, [59] used images captured simultaneously by a set of equidistant cameras with parallel axes, in vertical and horizontal lineups. The next step extracts a 3D model of the environment using computer vision techniques. Existing methods use depth maps as 2.5D representation of the scene's geometry. When the term "virtual reality" debuted at the end of the 1980s, the technology gained popularity because of its strange and interesting interface devices. However, with the technology now being considered more seriously, quality has become an important issue. At the very beginning, the virtual world displayed in primitive head-mounted displays seemed a "toy-like world" consisting of simple polygons. This naive computer graphics technology was based on 3D geometrical models. However, if we want to implement more complex worlds, this straightforward methodology has a serious limitation: defining a 3D model from huge numbers of polygons is exhaustive, time consuming work, and real-time drawing of the 3D model requires an expensive graphics workstation with a powerful geometry engine.

One promising strategy for world generation employs image-based rendering technology. This methodology uses 2D photographic images instead of 3D geometrical models. Worlds generated using this method have an advantage compared to those created using the polygon-based method-generating the same image quality is much easier. In addition, world generation is relatively easy following preparation of the 2D images. For example, the Virtual Dome system [26] generates a photorealistic world by rotating a camera once. The quality of the image remains basically independent of the rendering speed because everything is a simple bitmap. You can consider various sources for images, even existing 2D sources such as movies, videos, and prerendered CG images. What differentiates the conventional polygonbased technology and the 2D image-based technology? Each has advantages and disadvantages. For example, the former is very generic, capable of generating any worlds and objects by using a geometrical model from the beginning. Users encounter no limitation in interacting with the world. This is called "algorithm-intensive methodology". In contrast, the geometrical model is implicit in the latter. It produces quality as good as conventional 2D media, but interaction with the world is limited. The former strongly depends on CPU capability, and the latter depends on memory capacity. In other words, the latter requires a huge amount of data space because it has to handle redundant data. It also has disadvantages in networking, requiring very high bandwidth to share an image-based virtual world. The analogy to virtual-world generation is clear. The algorithm-intensive method corresponds to polygon-based computer graphics. By combining these methods, we should be able to generate more complex scenes of better quality. One of the simplest uses of the data-intensive method is just to arrange photographs, as with the Virtual Dome developed in the late 1980s [26] to provide a wide field of view to a remote user. The camera head continuously scans the surrounding space in order to capture a complete image of the area. The captured images are transmitted to the graphics workstation via a communication line. In the graphics workstation, a spherical shell is prepared as a virtual Omnimax screen onto which the transmitted images are texture mapped. With this configuration, a user wearing the HMD should be able to look around the rotating camera's world.

Several network communication aspects should be addressed for virtual environment (VE) applications; bandwidth, latency, distribution schemes, and reliability. The availability of network bandwidth determines a Virtual Environment VE's size and richness. As the number of participants increases, so do the bandwidth requirements. On local area networks, this has not proved a major issue because technologies such as standard Ethernet (10 Mbps) are relatively inexpensive and the number of users for LAN-based VEs limited. In contrast, for wide area networks, bandwidth have generally been limited to Tl (1.5 Mbps), but the potential user base is much larger through the Internet. However, networks are now becoming fast enough to be true extensions to the computer's backplane and to develop distributed VR applications. Distributed VR can require enormous bandwidth to support multiple users, video, audio, and the exchange of 3D graphics primitives and models in real time. Moreover, the data mix requires new protocols and techniques to handle data appropriately over a network link. The technologies providing these gains in performance blur the traditional distinction between local area and wide area networks.

There is also a convergence between networks that traditionally carried only voice and video over point-to-point links (circuit-switching) and those that handle packet-switched data. The actual number of VEs to take advantage of these high-speed networks has been small and associated with Grand Challenge (high-performance computing) problems. The Multidimensional Applications and Gigabit Internetwork Consortium (Magic) network is a gigabit-per-second ATM network that connects Minneapolis, Minnesota; Sioux Falls, South Dakota; Lawrence, Kansas; and Ft Leavenworth, Kansas. Magic allows a military commander to see 3D photorealistic computer-generated images of a very large interest area in real time, both from ground level and from the air, using data stored in a remote database. These images can be generated from elevation data (digital elevation maps), aerial photographs, building models, and vehicle models whose positions are updated in real time via the Global Positioning System. For example, a terrain database of Germany viewed on a workstation in Kansas receives images from California texture-mapped onto the terrain in real time. The network provides trunk speeds of 2.4 Gbps and access speeds of 622 Mbps, allowing an application to use a supercomputer (CM-5) to process data from a database at a second location and display the results on a workstation at a third location. The NASA Computational Aerosciences Project plans to use high-speed networks to support visualization of large computational fluid dynamics data sets by distributing processing onto several supercomputers across the United States. Gigabit networks will move supercomputer-generated actual geometries to remote graphics workstations for rendering. Similarly, the Electronic Visualization Laboratory at the University of Illinois has used a combination of Ethernet, Fiber Distributed Data Interface (FDDI), and High-Performance Parallel Interface (HIPPI) networks to develop a distributed VE application. The operator navigates through the VE using a CAVE (Cave Automatic Virtual Environment, a system that projects images on three walls or a hemicube for simulating "walkthroughs"), connected to Silicon Graphics workstations for rendering and control, which in turn connect to a CM-5 for actual simulation.

1.3 Computer networks, multimedia, and robotics

Intelligent robotics is concerned with the transfer of the manipulative capabilities of humans over a distance. Intelligent robotics consists of performing remote manipulative tasks through intelligent interfacing of human operator and robot arm by using visual information as well as other proprioceptive information.

A general robotic system (Figure 5) has a number of complex functional units that either perform some action on the environment or sense the result of previous actions [12, 25, 32, 49, 2] Intelligent robotics requires a specialized robotic system that is designed to satisfy a restricted class of tasks than a general robot. Intelligent robotics refers to a technology employing multi-jointed robot arms whose motion can be totally or partially controlled by a human operator that is remote or close by [35, 65, 11]. The principal long-term goal of intelligent robotics is to make human operators feel as if they are present at the workplace. As shown in Figure 6 an intelligent robot consists of a tele-robot system that makes the human operator almost as productive through remote control as on the scene. Therefore, an intelligent robotic system requires very large bandwidth because of the visual, sensual, and control information that it must continuously flow between the slave arm and the operator workstation [61]. These requirements are not difficult to satisfy if a dedicated communication media is provided but the benefit of intelligent robotics will be very much restricted to the limited domain. Old public networks like the telephone network cannot be used for the implementation of an effective intelligent robotics because of the limited bandwidth available. Transferring human manipulative capability over a public network will enable “Experts” like

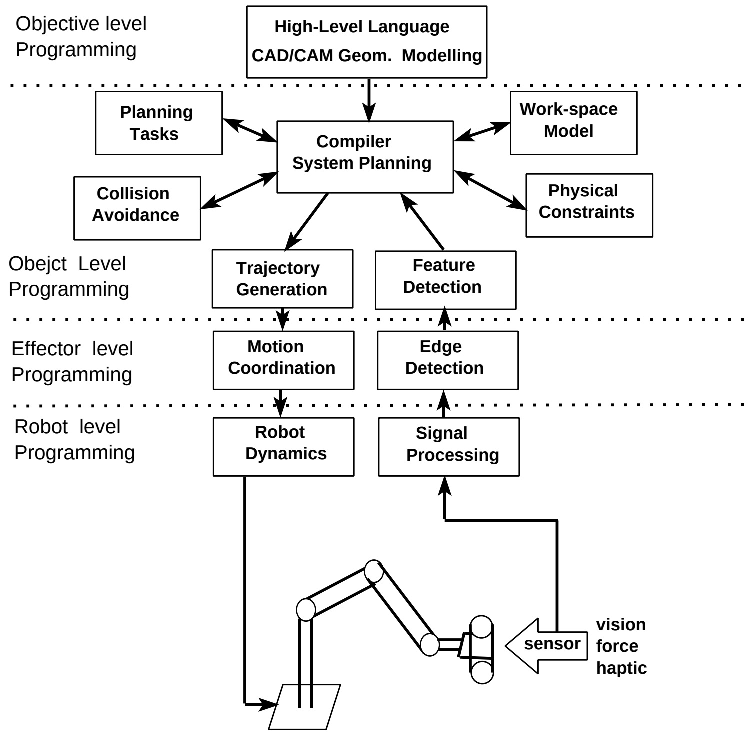


Figure 1.5: General Robotics System

surgeons to remotely operate especially in emergency cases from within a large geographical area. This technology is called *Telerobotics* which is one example of an intelligent robot system.

Telerobotics is based on combining two important ingredients: 1) an ergonomic and fully computerized man-machine interface, and 2) multimedia computer networks. A networked intelligent robotics will enable carrying out high speed data transfer of operator motion, sensory signals, and visual information. The use of computerized slave robots will provide an intelligent and functional interface to process and transfer force-feedback generated the slave arm, virtual-reality of slave scenes, in addition to traditional robot motion control. This will provide intensive interaction through use of continuous transfer of a variety of proprioceptive feedback, thus enabling high quality intelligent robotics.

A telerobotic system allows an operator to remotely perform manipulative tasks by using a master robot arm that is internetworked through LAN or WAN to a slave robot arm as shown in Figure 7. The telerobot consists of a master workstation and a slave workstation that are interconnected through a computer network to allow human operators performing working tasks in hazardous and hostile environments. Generally, telerobotics is concerned with the following functionalities:

1. Interfacing master and slave workstations so that to allow the operator to "feel" the reflected force feedback and to see the slave scene (stereo-vision) that are continuously sent from the slave workstation through network. Using the above retroceptive information, the operator can remotely manipulate the slave robot arm to achieve some task whose timely accomplishment requires high quality visual information and force feeling.

2. Providing a library of intelligent operator services to support the operator is to be designed and evaluated. Some of the functionalities are:

   (a) ability to remote control of orientation zooming of cameras in slave system,

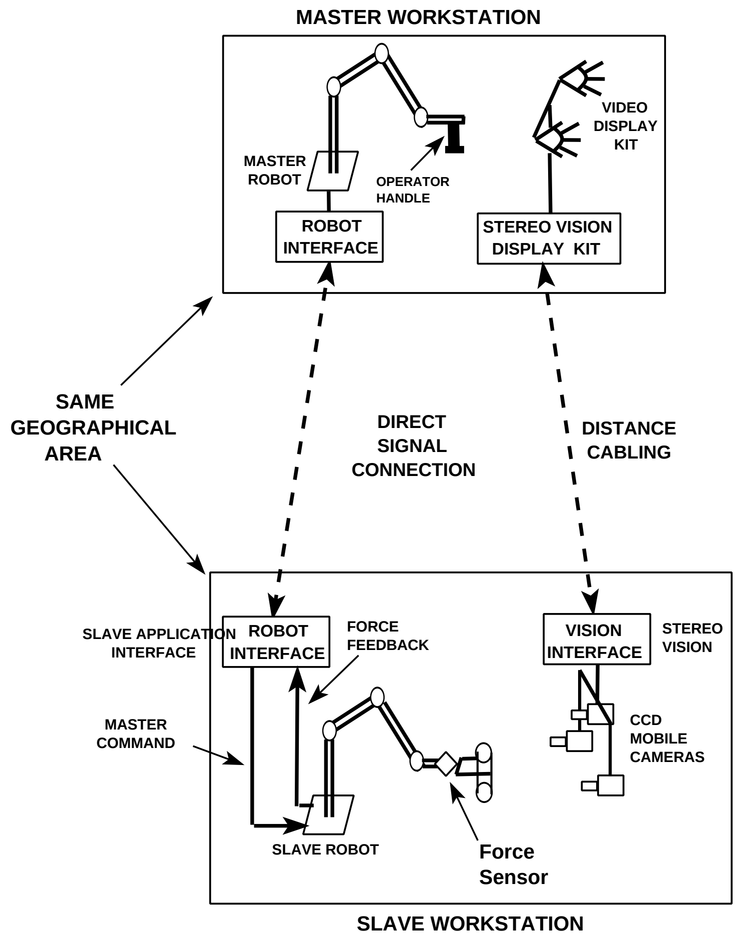


Figure 1.6: Telerobotics system: master and slave station are in one area

(b) ability to remotely activate local compliance loop for slave arm using force sensing to ensure no excessive force is exerted,

(c) ability to shift the master arm from a non-dexterous configuration to another without causing change to the positioning of slave arm, and

(d) ability of operator to interact (through master workstation) in real-time with slave workstation through network.

3. Studying the problems of time delay and delay jitter caused by network latency and their effects on telerobotics. Evaluate the performance of networked telerobotics and its operability in the presence of network delays.

This arrangement provides natural utilization of future multimedia networks in providing a number of critical services like remote surgery operations, emergency cases, tight safety conditions, and hostile environments. A new multimedia telerobotics system is to be designed for allowing humans to remotely extend their manipulative capabilities and skills over a computer network. For this a number of problems must be solved such as defining a general network interface for master and slave workstations, implementing network connectivity and transfer of control, providing force feedback and visual information, and handling the delay problem.

Currently developed multimedia communication and services can be efficiently used to provide specific telerobotics services. The wide spread of these communication services in

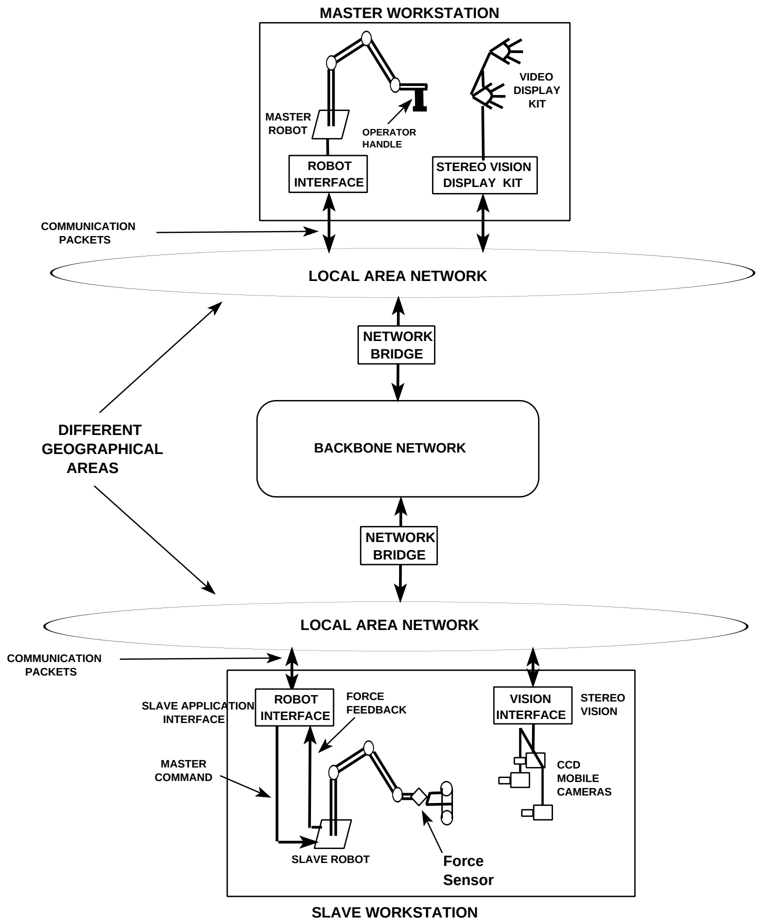


Figure 1.7: Future telerobotics in the wide area network

future computer communication will provide the needed backbone for the implementation and wide spread of telerobotics.

1.4 Medical robotics

With advances in computer technology, robotics can be efficiently used as an aid to people suffering from a wide range of physical disabilities with respect to the upper arms. The objective is to provide or recover the disabled some autonomy in performing daily living activities and to overcome his tetraplegic[1], myopthic[2], or poliomyeitic[3] disability. A rehabilitation robot would be designed so that it can be driven by means of voluntarily emitted signals that can be:

- mechanically generated in the case of translation of the motion of the eyes, motion of the head, or some motions of the shoulder.
- myoelectrically generated in the case of signals emitted from muscle contraction.

Given the difficulty of simultaneously emitting these signals in a voluntarily coordinated manner, therefore, a minimum number of instructions should be used to activate a rehabili-

[1]Amputation or absence of the upper members
[2]Muscle malfunction and deficiency
[3]Affection of the spinal cord by some diseases

tation robot. For this one needs to find out the best possible synergy for these signals and the language that uses them for building primitive instructions. In other words, an intelligent man-machine interface is needed to allow the disabled to autonomously perform a class of operations in the most ergonomic way.

Humans create passive or active tools that are adapted to their physical capabilities, the ergotherapeute[4] adapt supporting legs or tools to each specific physical handicap. Therefore, the problem is to adapt the rehabilitation robot to the condition of the largest possible category of disabled patients while keeping in mind that such a system must be operated with normal intellectual background. In this case, one of the important problem is to define the limit between the sophistication of the rehabilitation robot and that of the environment.

One important requirement for such a rehabilitation robot is an ergonomic [5] design which means that a medical robot should necessarily rely on a computer for understanding the task by using minimum number of actions from the patient. To provide a reliable system, the robot system should allow detection of operational errors, recovery, and modification of tasks. It is also highly desirable to provide the disabled some low level information as feedback of current action while keeping in mind the low cost of the whole system. The key point is that such a rehabilitation system is to make efficient use of computer flexibility, programmability, communicability, in assisting the disabled human.

For example eating from a plate of food requires repeatedly moving a spoon, which is attached to the robot, to the vicinity of the plate, fill the spoon with food, and move the spoon at fixed orientation to the vicinity of the mouth of the disabled. The disabled can take the food and repeat of the above cycle. Notice that the tasks involved above must be separated by some time break points that should be controlled by the disabled. For example the time for the disabled to take the food from the spoon. Also some of the above tasks can be taught once and replayed many times. For example moving the arm to the vicinity of the plate or the mouth. Other tasks must be directly controlled by the disabled. For this one needs to define a mapping from the spoon coordinate system to the head motion of the disabled. The objective is to provide a direct control of the spoon motion during the task of filling it with food from the plate. For example a very light head motion sensor or other sensors may enables the above motion mapping. It is clear that gaining quality control of motion of the robot requires mapping to some motion can still be generated by the disabled. Speech-based commands may be used to switch from one mode to another as well as for carrying out selection and directory search. The above man-machine interface allows the disabled autonomously performing a class of operations (eating, drinking, etc.) in the most ergonomic way.

Finally, a rehabilitation robotic system requires addressing a number of peripheral questions prior to its psychological acceptance by the disabled patients. Among these questions is the evaluation of its real utility, installation and utilization constraints, aesthetical aspects, ergonomic aspects, and the duration of its learning period.

1.4.1 Rehabilitation and robotics

Robot system design and artificial intelligence can be engineered as a powerful assistant to the disabled because they can extend human manipulative capability by using few voluntarily emitted signals. In the following we review some of the muscle disease that may cause the disability with respect to upper and lower members.

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[4]biomedical engineers that design and interface prothesises to amputed or defective members, prothesis: a device that can substitute a missing member, orthesis a device that can improve the deficiency of a member

[5]Describe a system that require the least muscular work

The human body has more than 600 separate muscles that represent 40% of the body weight. A muscle consists of thousands of fibers which course for variable distance. Diseases may affect only one part of the fiber, leaving the remainder to atrophy, degenerate, or regenerate depending on the severity of the disease. The muscle fibers are attached at their ends to tendon fibers, which in turn connect them to the skeleton. Each muscle fiber receives a nerve from a motor nerve cell in the anterior horn of the spinal cord. Chemical (Acetylcholine) is liberated from vesicles in the nerve terminals and transmit the nerve impulse to the muscle fiber.

The following are the most frequent types of disorders that may affect the muscle due to congenital or muscle diseases:

- Spontaneous activity during complete relaxation (Myotonic muscle)
- Angulated muscle that is functionally isolated (Fibrillation)
- Involuntary contraction of a motor unit in isolation (Fasciculation)
- Abnormalities in motor units such as the amplitude, duration, and shape of a motor unit potential (myopathies).
  - Reduced amplitude and duration of action
  - Enlarged potential in grouped fibers
  - Decrease in the number of muscle fibers (dystrophis)
  - Progressive reduction or increment with successive contractions (myasthenia)
  - General weakness and paralysis
  - Qualitative changes in speed during contractions and relaxation (myoedema)
  - Muscle pain (polymyosities)

All these disorders represent what is called chronic myopathies that is classified as partial or total paralysis.

For the severely disabled, with little or no use of their hands, the ability to manipulate items can greatly increase their independence. Robotics can provide the needed manipulative ability because of its flexibility and the wide range of operations. A *Rehabilitation Robot* can be engineered as an extension to a disabled person with appropriate mental faculties but with physical disabilities, whether traumatic or congenital in origin.

Currently, NASA-JPL is leading a group of Universities and Industries for developing and enhancing strategies for rehabilitation of individuals with spinal cord injury. This will allow the use of the experience learned from space robotics and its application to neural repair and rehabilitation problems resulting from traumatic brain and spinal cord injury.

Robotics can return voluntary actions because each person regardless of the severity of paralysis or amputation has certain reactionary points [52]. They also have applicable sensory points which can be acted upon. Through adaptation, the reactionary points can be given a code which can control many functions or modes. Robotics can also add the equivalent of artificial instinct which can provide automatic safety attributes. Modes can combine with the voluntary and instinctive attributes, to provide automatic features such as balancing a glass of water while constantly monitoring and obeying new commands, and surveying the surroundings. However, the use of robot manipulators requires an excellent dexterity and cognitive efforts not often available among the concerned users population [18]. Preprogrammed gestures and a control method [33, 56] that offers shared control between the human and the machine may improve the execution of complex tasks [53].

A robotic manipulator could be built into a stationary or mobile workstation such as a wheelchair or a wheeled trolley [42]. Generally, the system can operate both under the direct control of the user and the automatic replay of previously programmed sequence of movements. These operations may be set up by the user to perform regularly needed tasks. Control may range from a simple switch input (eg hand switch, suck/puff switch or joystick) to a scanning menu system. More generally, the rehabilitation stations are generally studied with respect to their user control strategies, safety, and aesthetics.

Wheelchair-mounted rehabilitation service robot [15, 58] provides the disabled enhanced reliability as well as the feelings of safety and confidence. The Wheelchair assists the disabled with a set of autonomous and manual manipulative tasks (passive and active). See [19] for details of passive and active modes. The autonomous tasks are grasping an object on the table, grasping an object on the floor, and manipulating a switch on the wall. Daily life tasks like eating, drinking, or playing are required to provide the needed level of autonomy to the disabled. Long term targeted tasks [58] are cooking, washing, shaving, and teeth cleaning. Safety is important for anything which will be used in proximity to humans, particularly away from supervision. This is achieved primarily by the use of low powered motors as part of an inherently safe mechanical and electrical design.

Most workstations are laboratory prototypes with a few commercialized products and, in spite of efforts of the developers, the reliability was the weak point of these systems. Additional design work is needed [16, 28, 44] to eliminate problems of inadequate reliability on rehabilitation robots. A lot of effort is being deployed in the development of inexpensive workstations [13, 39] by a number of manufacturer of industrial robots that are currently developing rehabilitation robots [16]. Recent advances in personal computer technology, networking, and multimedia must be used in solving the above problems.

The objective is to design a rehabilitation robotic system which allows a person with disability in the upper arms to perform a class of real-life tasks in an autonomous way and at a reasonable effort. Such a system requires an intelligent man-machine interface that is based on two fundamental features: 1) an intermediate man-machine language, and 2) a few voluntarily generated signals out of the disabled to be used as language primitives.

The man-machine language serves as an intermediate between the disabled and the machine which is a robot controlled by a personal computer. The language has primitives to perform fundamental operations and to ensure full control of the robot arm with the least effort and description. Each language primitive describe the way a function must operate in terms of modules and sequencing. For example, teaching the robot a task on moving a cup of water close to the mouth requires the following sequence: 1) move the arm to grasp the cup, 2) move the arm-cup to the mouth (teaching/automatic), 3) activate slow rotation of the cup (direct control), 4) return cup to its previous place (teaching/automatic).

The first operation requires direct control of the robot with possible correction of the robot position and orientation. This can be done by allowing direct control through continuous head motion signal analysis and interpretation of these signals as corrective requests. The second operation can be done in an automatic way because the mouth position can be previously taught and then the task is to move the arm holding the cup to that position. The third operation requires direct control of the robot by using some interaction between the emitted head motion signals and the rate of rotation of the cup. One may also use a straw to drink the water without the need to rotate the cup. Finally, returning the cup back to the table can be done in an automatic way because the original location of the cup is kept into the computer memory.

One can define the general requirement of such a rehabilitation robot as an intermediate man-machine language that is driven by few voluntarily generated signals out of the disabled. To some extent the language can be general and universal which means that completely different kind of input signals can be used in the operations. This might be a very useful aspect because such a rehabilitation robot must necessarily have some personalized aspects. Processing the voluntarily emitted signal out of the disabled is carried out by a module called the *Language Driver*. The rehabilitation robot has two-level: (1) a language and (2) a driver. The language is a set of modes, functions, tasks, operations together with their functionalities and rules of activation. The driver recognizes a set of voluntarily emitted signals (head motion and speech) and converts them into actions that affect the robot arm and the computer system. The separation between the language and the driver provides useful flexibility because the language can be driven using different drivers that use totally different voluntarily generated signals with the same language system. This increases flexibility and ability to upgrade with more sophisticated biomedical interfaces.

It is believed that a human generally has great capability to learn operations that have direct link to specific motion or actions. By providing the means to define and modify the low level manipulative operations we internationally rely on human to compose primitive tasks into meaningful gestures and operations that make life easier for the disabled.

With advances in computer technology, robotics can be efficiently used as an aid to people suffering from disability in the upper arms. Example of such disabilities are the amputation or absence (congenital) of the upper members, muscle malfunction, and general motor deficiency. For the disabled the ability to manipulate items by using a robot arm can greatly increase his independence in daily living activities. An intelligent man-machine interface may allow the disabled to autonomously perform a class of operations (eating, drinking, etc.) in the most ergonomic way. A disabled with normal mental faculties will be able to teach new operations, modify previously defined operations, and carry out selective execution. The accurate control of some robot tasks requires direct control by the disabled through the motion of one of his active organs. By combining robotics, computers, and multimedia robot-based rehabilitation systems are expected to greatly improve or replace the lost ability of the disabled as well as facilitating his integration with the environment, giving the disabled increased independence and reduced reliance upon carer.

1.5 Space robotics

The NASA [6] is developing a space program concentrating of the design of *Free Flying Services*. This segment of the program is focussed on the development of space robotics for eventual application to on-orbit satellite servicing by free-flying servicing robots. The purpose of this segment of the program is to focus the development of component technologies into applications and environments which will demonstrate their utility and additional capability when incorporated into operational systems. These technologies include virtual reality telerobotics, advanced display technologies, proximity sensing for perception technologies, and robotic flaw detection. The target applications include such tasks as repair of free-flying small satellites, and ground-based control of robotic services. Each of these areas have been identified by the potential space robotics user community as applications where space robotics will be necessary to satisfy their planned requirements. This user community includes the External Work System and anticipated commercial space system developers. The program includes the following space sub-systems:

[6] NASA Web site

1. The ranger telerobotic flight experiment.
2. The ranger automated visual inspection system.
3. The telerobotics / VR control of free flying robots.
4. The dexterous arm control for ranger flight experiment.
5. Free flying camera robots For enhanced EVA performance external work system.
6. Space operations.

1.5.1 The ranger telerobotic flight experiment

In June 1992, the decision was made to actively pursue the development of the Ranger Telerobotic Flight Experiment (TFX), as proposed by the University of Maryland Space Systems Laboratory. This project includes the development of neutral buoyancy (floating) and flight prototypes for a class of low-cost expendable telerobots designed for research and servicing in space, beyond the space station orbit. The vehicle will be equipped with four manipulators: two 7-dof arms for bilateral dexterous manipulation; a 7-dof manipulator for grappling at the local worksite; and a 6-dof arm for positioning a pair of stereo video cameras giving primary feedback to the remote operator. A second stereo camera pair mounted on the vehicle centerline will provide a stable visual reference for free-flight maneuvering, and ultimately feed a vision system for autonomous vehicle docking.

Much of the design and construction of the Ranger Neutral Buoyancy (NB) Vehicle was completed in FY 93. In FY 94, the manipulators were assembled and integrated onto the completed mobility base. In FY95, the Ranger NB vehicle was outfitted with upgraded manipulator electronics and operated in the University of Maryland (UMd) Neutral Buoyancy Research Facility. The completed Ranger NB vehicle, while providing telerobotic operational data, will also be used to develop and verify algorithms, software, and experiment designs for the space flight experiment.

The Ranger TFX spacecraft design is strongly coupled to the Ranger NBV design. In FY94, several system trades were performed to determine the overall scope and configuration of the TFX vehicle. In FY95, preliminary design of the spacecraft subsystems was performed and long-lead items were identified. In FY96, component acquisition and subsystem construction will be performed, leading up to system integration and test in FY97. The TFX mission is planned for flight early in FY98.

1.5.2 The ranger automated visual inspection system

Automated robotic inspection of space platforms such as Space Station is expected to be an important element to offload time consuming inspection activities from astronauts. Jet Propulsion Laboratory recently developed such a remote surface inspection (RSI) system demonstrated successfully on the ground in a constrained lab environment. The system, however, needs further evaluations/enhancements to be robust for practical use in space applications. The objectives of this task are to 1) evaluate and enhance the existing JPL automated surface inspection technology and 2) apply this technology to the Ranger TFX mission Phase 3 Visual Inspection Task to assess/validate the telerobotic automated inspection capability in real space operation lighting conditions. The inspection taskboards will be three-dimensional with different surface textures, and will be used for both ground-based pre-flight and actual Ranger flight tests.

The automated inspection software package will be evaluated and enhanced to be robust under 1) varying ambient sunlighting and under 2) varying image mis-registrations. At present, we will assume that only on/off controllable continuous lighting will be available for the actual Ranger flight, which will achieve about 80% of our evaluation/validation goals relative to the flight inspection test equipped with electronic shuttering/strobe lighting. The image registration problem is not affected by the absence of electronic shuttering/strobe lighting. Actual video images collected under varying sunlight angles (including shadowed or dark portions of the orbit) can still determine the quality of the automated inspection algorithm quantitatively below a certain level of sunlight illumination. Further, simulated strobe lighting can be added to the video images collected during the actual Ranger flight to evaluate the dynamic working range of the automated visual inspection algorithm. University of Maryland may later opt to add electronic shuttering/strobe lighting.
The focus and Directions of the above project are:

1. FY 1996: Evaluate/enhance the existing automated inspection software package. Design a Ranger inspection board mockup and build two (one for JPL test and the other for Ranger delivery). Define onboard and ground-site requirements for the Ranger flight inspection experiment in coordination with the University of Maryland Ranger TFX team. Define inspection scenario, and develop inspection task software including user interface and command sequences consisting of arm motion control, light on/off, and image captures. Deliver a taskboard mockup, inspection task software, and inspection scenario to the University of Maryland Ranger Program for Neutral Buoyance test by June 1996.

2. FY 1997: Deliver a revised inspection taskboard for the Ranger flight by December 1996. Complete the development of an enhanced automated inspection software package and perform ground baseline pre-flight tests by June 1997. Analyze, on the ground, actual inspection experiments in the flight and post-flight operations. Document the results.

1.5.3 Telerobotics / VR control of free-flying robots

The objective of this research task is to add a telepresence/virtual reality control interface to a free-flying robot. This interface will initially provide advanced teleoperation and supervisory control capability to the Ranger NB (Space Systems Laboratory, Univ. of Md.) by augmenting existing control stations. Subsequent work will provide telepresence/virtual reality control capability to the Ranger TFX telerobotic flight experiment.

The Ranger NB vehicle is an extremely complex telerobot, offering 32 degrees-of-freedom for operator control. To productively use this system, it will be critical for operators to have an effective control interface. In particular, the interface must provide support to the operator for visualizing the workspace, for efficiently displaying vehicle state, and for handling system latencies such as communications delay. In addition, the interface must enable higher human performance while reducing operator fatigue and stress. One approach which appears to satisfy these requirements is the telepresence/virtual reality control interface.

During the past three years, the Intelligent Mechanisms Group (IMG) has been developing control interfaces utilizing telepresence and virtual reality technology. These interfaces seek to provide robotic systems with high-fidelity telepresence capabilities and allow users to more easily interact with remote devices. By utilizing real-time interactive computer graphics, stereoscopic video and stereoscopic displays, telepresence/virtual reality interfaces enable users to efficiently manage and visualize complex systems. As a result, such interfaces can dramatically improve human teleoperation performance, particularly in the presence of time-delays.

The approach is to provide for a transfer of control interface technology from the Ames' IMG to the University of Md. SSL. This transfer will involve the augmentation of existing SSL operator stations with telepresence and virtual environment subsystems. Specifically, the IMG will provide technology developed at ARC which utilizes real-time interactive computer graphics and stereoscopic video displays. The work will be conducted in a two phase project.

In the first phase, a telepresence/virtual reality interface will be developed for the Ranger NB system. This interface will provide the operator with real-time visualization of the Ranger NB system state and worksite. The focus of this phase will be to directly enhance the capability and to improve the performance of human operators in a research environment.

In the second phase, refinements to the telepresence/virtual reality interface will be developed to support the Ranger TFX flight experiment. These refinements will include the development of orbital dynamic vehicle models and predictive displays for handling system latencies in the presence of communications delays. It is expected that the control interface project will have a minimal impact on the SSL's on-going Ranger NB and Ranger TFX development process. The initial work will be performed at ARC and leverage existing IMG resources and personnel. This will be followed by integration with Ranger subsystems, which will be conducted jointly by the IMG and the SSL.

1.5.4 The ranger dexterous arm control

The goal of this task is to augment the operational capabilities of the dexterous arms in the Ranger Flight Experiment. These new capabilities will be developed within the framework of Configuration Control, which has been developed at JPL and selected for implementation on the Ranger arms.

The approach is to Develop the capability of on-line collision detection and avoidance for the Ranger dexterous arms. This capability does not currently exist in the Ranger baseline control system, and erroneous operator commands can cause collision between the dexterous arms and the camera and grapple arms, the base, or the task board. The performance improvement due to this added capability will be measured in two ways. First, it will enable a broader range of tasks to be executed safely, such as collision-free reach inside a constricted space or opening. Second, it will cause a reduction in the Ranger operation time by 50%, since several possible motions with potential collision are not executed. Finally, this capability will increase the safety of the Ranger during the operation of the arms, a feature which is vital to the success of the Ranger mission.

Provide the ground operator a software tool for proper placement of the Ranger base. This algorithm will ensure that both dexterous arms reach the task site and the useful workspace volume is maximized. The algorithm will take into account the fact that the Ranger base is attached to the task site by the grapple arm. At present, the placement of the Ranger base is done by the ground operator in an iterative trial-and-error fashion. The performance improvement due to this added capability is expected to be a reduction by 30% of the Ranger operation time.

Conduct proof-of-concept experiments to demonstrate the collision detection/ avoidance and optimal base placement capabilities. The RSI Laboratory at JPL is equipped with two mobile RRC arms which have very similar kinematics to the Ranger arms, as well as a similar real-time computing platform. This facility will be used for final testing of the JPL algorithms before implementation on the Ranger flight and ground computers.

The above capabilities will considerably enhance the robustness and reliability of the

Ranger arm control system, and will significantly expand the range of tasks that can be accomplished in the Ranger Flight Experiment. A series of technology experiments are planned to demonstrate the collision detection/ avoidance and base placement capabilities on the wet-Ranger while operating in the Neutral Buoyancy Tank at SSL.

The Focus and Directions of the project are:

1. FY 1995: Develop and implement the collision detection/avoidance capability for the Ranger to enable robust and reliable task execution. Perform proof-of- concept graphical simulations on the Silicon Graphics IRIS Workstation at JPL using the kinematic model of the Ranger 7-dof arms. Deliver the JPL-developed software modules to the Ranger Project.

2. FY 1996: Develop and implement the optimal base placement capability for the Ranger to enable execution of single-arm and dual-arm tasks. Conduct a series of technology demonstrations at JPL to validate the collision detection/avoidance and optimal base placement capabilities experimentally. Quantify the operational improvement of the Ranger with the augmented capabilities of automated collision avoidance and base placement. Deliver the software modules to the Ranger Project.

1.5.5 The free flying camera robots for enhanced EVA

Many Space Station operations will occur outside of direct line-of-sight of the habitated modules. Due to cost reduction exercises, the number and placement of mounting sites for external video cameras on Space Station will be highly constrained. Since many Space Station servicing tasks will be performed EVA, this implies that highly complex EVA operations may well take place without any capability for monitoring inside the modules or on earth. These operations could be significantly enhanced if a free-flying camera platform were available to send the desired images back. This same device could also be used to increase the performance of the robotic elements of the Mobile Work Station, by providing auxiliary views to remote operators on the station or on the ground.

This effort, performed by a team of the University of Maryland and the Johnson Space Center (JSC), will focus on the external operations, realistic trajectories, and crew interfaces. The Supplemental Camera and Mobility Platform (SCAMP) will be enhanced by upgrading the video camera to a stereo pair, and by adding sensors for the 3DAPS navigation system. Flight control software will be upgraded to incorporate this new sensor data, which will allow autonomous station-keeping or tracking of dynamic targets. Also under the initial efforts, an inexpensive, low-fidelity simulation of the Space Station pre-integrated truss will be developed for the Neutral Buoyancy Research Facility. During this time, JSC will be developing algorithms for realistic flight trajectories, and will develop a crew interface for SCAMP, based on existing training environments (Space Shuttle and Space Station mockups, and the IGOAL virtual reality laboratory).

In initial tests, the University of Maryland NBRF will simulate the space station environment, with test subjects wearing the MARS suit simulators developed in the prior year under internal funding of the University of Maryland. Operators at JSC, including flight crew, will control SCAMP over the Internet to monitor test operations, with video return to JSC over a satellite link with compressed Internet video as a backup option. The outcome of these tests will be to demonstrate the safety aspects and monitoring capabilities of a free-flying platform, and to develop a constituency for this type of telerobot among the operational community.

In following tests, SCAMP and its derivative vehicles will be used in neutral buoyancy simulations to monitor operational EVAs, particularly Space Station development EVA simulations. These tests will incorporate University of Maryland software for autonomous dynamic tracking and predefined view angles, and will provide additional impetus for development of an operational flight unit. The ultimate goal of this research will be to demonstrate free-flying robotics in a high-fidelity neutral buoyancy environment, with the vehicle behaving dynamically as if it were in space, and incorporating advanced levels of autonomy to minimize operator workload.

1.5.6 Space operations

The development of new technologies for space telerobotics brings with it a concomitant requirement for understanding the impact of that technology on the operational capabilities of the eventual telerobotic system. Addressing this area of space telerobotic operations is the primary focus of the University of Maryland Space Systems Laboratory (SSL). During its initial years of operation at the Massachusetts Institute of Technology, the SSL pioneered the development of analytical models for neutral buoyancy simulation, and performed extensive tests on extra-vehicular operations, leading to the Experimental Assembly of Structures in EVA (EASE) tests on STS 61-B in late 1985.

Since that time, the SSL has focused primarily on space telerobotic operations, with emphasis on neutral buoyancy simulations of integrated EVA/telerobotic work sites. The Beam Assembly Teleoperator (BAT) has performed structural assembly of both EASE and Space Station truss structures, as well as tests of Hubble Space Telescope servicing, both alone and in conjunction with EVA subjects. The Multimode Proximity Operations Device (MPOD) has performed a number of tasks relevant for orbital maneuvering vehicle-class spacecraft, and has demonstrated the utility of manned astronaut support vehicles for extended EVA capabilities. The Apparatus for Space TeleRobotics Operations (ASTRO) has been used to research three-dimensional positioning and station keeping systems. The Stewart Platform Augmented Manipulator (SPAM) replicates the functionality of the Space Shuttle Remote Manipulator System, with improvements in fine end-point positioning based on the Stewart Platform wrist. The Supplemental Camera and Maneuvering Platform (SCAMP) provides operator-controllable external video views, and has been used for tests of single-operator control of multiple free-flying telerobots.

The focus and directions of the above project are:

1. FY94 Collect data base on advanced telerobotic operations using neutral buoyancy; develop an advanced work site simulation for quantifying performance of integrated telerobotic operations; test EVA/telerobotic cooperative tasks at NASA Marshall Neutral Buoyancy Simulator.

2. FY95 Operate existing telerobotic systems to collect data base on advanced telerobotic operations in neutral buoyancy; develop an advanced work site simulation for integrated telerobotic operations; test EVA/telerobotic cooperative tasks at NASA Marshall Neutral Buoyancy Simulator.

3. FY96 Utilize Ranger technology for rapid prototyping and operations testing of advances concepts for telerobotic and EVA/telerobotic space operations.

4. FY97 Use results from Ranger flight experiment and Ranger NBV to develop extensive data base on telerobotic performance in space operations tasks.

Exercises

1. Define a robot system. What are the main modules in a robot system. Shortly define the function of each module and specify its inputs and outputs.

2. Define a robotic motion coordination system by using the concept of geometric model and its inverse. Explain why the motion coordination system is one critical component of a robot arm. Give the block-diagram of a 6 d.o.f robot arm for which all links are revolute. How one can solve the problem of singular positions and the problem of multiple solutions in the inverse geometric model.

3. Define a telerobotic system and its main components. Give the block-diagram of a telerobot that consists of a master arm, a slave arm, and a network. Discuss the need for visual information and force feedback in telerobotics. What would be the effects of communication delays in telerobotics.

4. Search on the Internet the current technology for getting 3D stereo vision between two symmetric PCs that are interconnected by using a LAN and a WAN. Determine the hardware and software needed for the above task and discuss the operability and cost of the above equipment.

5. Summarize the objectives of the NASA space program and shortly describe each of its six experiments.

1.6 Conclusion

With advances in computer communication technology, multimedia services are rapidly gaining ground with applications requiring high speed simultaneous transfer of on-line video images, speech signals, and data. The main benefit for this new information network is a class of multimedia applications which require large bandwidth and high speed data transfer. For example teleconferencing which enables two persons or more which are separated by large distance to hold conference involving continuous exchange of video, speech, and data information. We also notice that most small computer systems and new microprocessors are provided with multimedia capability. The critical importance of the information network is related to its expected wide spread, low cost, and operability. This new information network is currently replacing the traditional international telephone network. The ability of computer networks to provide high bandwidth reliable communication is important not only for the transfer of visual and speech information but also to the transfer of human manipulative capability through the use of robot arms. By combining robotics, computers, and multimedia networked robotics is expected to (1) greatly improve human ability to remote operation, (2) facilitate human integration and interaction with the environment, and (3) increase capability for tele-operations in space and hostile environment.

Recommended books:

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2. L. Sciavicco, B. Siciliano, "Modeling and control of robot manipulators", MacGraw-Hill, New York, 1996.

3. J. Demiris (Univ. Edinburgh) and A. Birk, “Robot Learning - An Interdisciplinary Approach”, Edited by (Vrije Universiteit Brussel), 220pp, May 2000, (ISBN: 981-02-4320-0).

4. J. H. Andreae (Univ. Canterbury), “Associative Learning for a Robot Intelligence”, 360pp, Sept 1998, (ISBN: 1-86094-132-x).

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