Cobots in Materials Handling

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In May 1995 Northwestern University and General Motors Corporation began a five year project toward the creation of "Intelligent Assist Devices" (IADs). The project envisioned a class of devices that would improve ergonomic working conditions, product quality, and productivity by applying ideas from robotics to the Manual Assist Devices that are widely used in materials handling.

The project was motivated by issues in automobile final assembly, an area which has seen only limited automation. Human workers bring a number of capabilities to assembly that are difficult to match with automation, such as parts-picking from unstructured environments, identifying defective parts, fitting parts together despite minor shape variation, pushing aside interfering cable bundles or fabric, and many more. Redesigning the assembly process to eliminate the need for such skills is not seen as cost-effective or desirable. However in recent years the size and weight of the components assembled into an automobile body has increased as more subassembly has been done off the main assembly line. Larger subassemblies, and an increasing awareness of the significance and frequency of ergonomic injuries, have led to a need for mechanical assistance of various forms. Manual Assist Devices are typically based on hoists, overhead x-y rail systems, or articulated arms. Their translational motion is usually unpowered, and they incorporate little if any computational logic.

Manual Assist Devices increase the friction and inertia that a worker must cope with in completing a task. It is not uncommon for an assist device to have a moving mass ten times that of its payload. Where motion of the payload must be restricted to avoid collisions, mechanical guides or stops are used. For sophisticated insertions, shaped guide rails may be constructed to define the path of the payload as it approaches its assembly location. Such manual assist devices can offer ergonomic benefits, but they also have significant drawbacks in maneuverability, productivity, and lack of programmability.

In response to the limitations of Manual Assist Devices, a central goal of the GM/Northwestern project was to find a way of implementing large-scale virtual surfaces, which we proposed as a primary form of interface between human worker and computer in Intelligent Assist Devices. Virtual surfaces promised to provide physical guidance for workpart motion, without requiring that the guiding surface be physically embodied as a solid object such as a rail.

The development of cobots[5] provided a programmable means of setting up large-scale virtual surfaces. When an operator pushes a payload up against a virtual surface established by a cobot, the payload's motion is confined to follow that surface, just as if it had run into a frictionless guide rail. When the payload is pulled away from the virtual surface, operator and payload motion is unconstrained ("free mode").

Cobots in materials handling applications are thus a departure from the industrial paradigm of independently competent robots isolated from human contact. They also differ also from telerobotics, in which a human operator controls a remote manipulator through what is essentially an information-only

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[5] Nonholonomic Haptic Display, J. Edward Colgate, Michael Peshkin, Witaya Wannasuphoprasit, Proceedings of the IEEE 1996 Int'l Conference on Robotics and Automation, Minneapolis (Best Conference Paper Award)

link. The cobot concept supposes that it is not *amplification of human power* that is most needed, but rather *shared control:* both human and robot are in “hand on” contact with the payload

An example of the use of virtual surfaces

The task of moving a dashboard assembly suspended from an x-y rail system into a car body through a door opening could benefit from a virtual surface, both in terms of productivity and ergonomics. The taskspace includes two dimensions of horizontal translational motion, as well as orientation about a vertical axis, and a “roll” axis (about the long axis of the dashboard) which must be employed to prevent interference with the doorframe as the dashboard is inserted. A single fluid motion along a curved virtual surface through four-space, guided by computer, could replace a struggle to contend with four axes at once.

Even if all sources of friction could be removed, and a task takes place in a horizontal plane so that lifting is not required, maneuvering a massive payload can nevertheless be a significant ergonomic problem. Redirecting a payload’s motion once it is moving at constant speed is energetically neutral, but still requires large forces from the operator. Furthermore, these “steering” forces tend to involve the muscles of the back and arms, rather than the large muscles of the lower body. In the field of ergonomics, the term “inertia management” refers to the issues which arise due to payload mass.

High quality virtual surfaces can greatly reduce the human force needed to control the motion of a massive payload. A worker can take advantage of a curved virtual surface by sliding a payload along it and allowing the forces of the virtual surface to redirect the motion of the payload, rather than exerting large muscular forces.

This example illustrates the potential benefits of virtual surfaces due to their information content (coordinating multiple degrees of freedom) and also their ergonomic benefit.

Why not use joint brakes or powered joints for virtual surfaces?

Ideal qualities of a virtual surface are that it be **hard** – a force perpendicular to the surface should cause little penetration of the surface; **strong** – it should be able to withstand large forces; **smooth** – the velocity of the endpoint should be tangent to the surface at all times; **frictionless** – motion tangent to the surface should be unimpeded by the surface; and **abrupt** – at any distance away from the virtual surface, motion in any direction should be unimpeded: the transition from a “free” region to a virtual surface should be instantaneous.

Physical implementation of virtual surfaces has been approached in several ways. Powered actuators have been explored by many workers, and are extensively discussed in this book. It has also been proposed to use brakes, particularly brakes in which braking torque can be varied continuously[6], to prevent penetration of a virtual surface. Such brakes may be used in combination with motors, or in place of any other joint actuators.

Joint brakes have difficulty displaying virtual surfaces that have the desirable property of smoothness. In the fortuitous circumstance that the endpoint motion caused by one joint alone is tangent to a virtual surface, that joint’s brake can be left unactivated (and the joint free) while the other brakes are fully locked. This displays a strong smooth and frictionless surface. In the general case however no such special alignment will occur, and all brakes must be partially activated. Keeping the endpoint near the virtual surface despite endpoint forces requires active control of the brakes in response to small penetrations of the surface. This has proven to be difficult (although one cause may be the non-ideal behavior of currently available brakes.) Alternatively, the brakes can be used in a “full-on or full-off” mode, changing the

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[6] M. Russo and A. Tadros, “Controlling Dissipative Magnetic Particle Brakes in Force Reflective Devices, ASME Winter Annual Meeting, Anaheim, CA, November 13, 1992

physically allowed direction of endpoint motion at frequent intervals and thereby approximating the virtual surface by a sawtooth combination of allowed motions of individual joints. Not surprisingly this results in a perceptually jagged surface.

On a more fundamental level, the use of any brake involves the dissipation of energy. Even if brakes could be controlled such that the displayed virtual surfaces were smooth, sliding along such a surface would require a higher force than moving the endpoint through the free-space region adjacent to the virtual surface, in which no brakes are activated. We argue that a desirable property of a virtual surface is that it be not only smooth but also frictionless, or of low friction. In large scale tasks, such as moving a payload into an automobile body, the experience of purely mechanical assist devices shows that friction is a significant hindrance. If a guiding surface is to be of use in making such a task faster and more accurate, it must be a low-friction surface. A surface that dissipates the human operator's energy of motion may be useful as a boundary to be avoided, or to prevent collisions, but the operator will not be able to take intentional advantage of it by sliding the payload along it.

Davis[7], Gomes[8], and Book have built a passive 2 degree of freedom manipulator with brakes on each joint, and also a third brake on a differential connected to the two joints. The differential and its brake provide an additional mechanically enforced high quality virtual surface, in which the motion of the two joints is constrained to be equal when the brake is locked. It might be hoped that the difficulties of approximating an arbitrary virtual surface might be reduced by a more fine-grained set of intrinsic surfaces.

Another approach is that of Delnondedieu[9,10] and Troccaz[11] who have built PADyC, a "passive arm with dynamic constraints". Each passive joint is equipped with two unilateral clutches, by which the joint's angular velocity is mechanically constrained to lie between two limits: $\omega_1<\omega_{joint}<\omega_2$. The reference angular velocities ω_1 and ω_2 are produced by servomotors. As the manipulator approaches a defined virtual surface, the maximum allowed joint velocities in directions approaching the surface are reduced, reaching zero as the surface is contacted. In practice, smoothness and low friction are not achieved.

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[7] Davis, Hurley and Wayne Book, "Passive Torque Control of a Redundantly Actuated Manipulator" Proceedings of the 1997 American Control Conference, June 4-6, 1997, Albuquerque, NM, 5 pp (on CD ROM).

[8] Gomes, Mario and Wayne Book, "Control Approaches for a Dissipative, Passive, Trajectory-Enhancing Robot," Proceedings of the 1997 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, paper 92, 6 pp (on CD ROM), June 16-20, 1997, Tokyo, Japan.

[9] Yves Delnondedieu, Jocelyne Troccaz, "Synergistic robots for surgery: the algorithmic view of this approach", WAFR'98, Third International Workshop on Algorithmic Foundations of Robotics, March 5-7, 1998, Rice University, Houston, Texas

[10] Yves Delnondedieu , PhD Thesis "Un Robot à Sécurité Passive", Sept. 1998, Universite Joseph Fourier, Grenoble

[11] Troccaz, J., Lavallee, S., & Hellion, E.. (1993). "PADyC: A passive arm with dynamic constraints". Int. Conf. on Advanced Robotics, pp. 361-366, Tokyo, November 1993, JIRA

Wheeled cobots with planar workspaces

When robots are used to enforce virtual surfaces, the robot's joint motors must resist operator and payload forces that would violate the constraint surface. Cobots, by comparison, do not use joint actuators to enforce virtual surfaces. Instead they employ nonholonomic joints. These joints redirect disallowed motions, rather than fight them.

The simplest cobot, which nevertheless exhibits all essential behaviors, is the "unicycle" cobot shown in Figure 1. It has a two-dimensional (planar) workspace. Virtual constraint surfaces, defined in software, delimit excluded areas of the plane.

The cobot mechanism consists of a free-rolling wheel in contact with a working surface. The wheel's rolling velocity is monitored by an encoder, but it is not driven by a motor. The motor in the figure simply steers the wheel. No amount of malevolent steering by the control computer can cause the cobot to move on its own. Only the operator can cause it to move, by applying forces to the handle. A force sensor monitors these user-forces.

The unicycle cobot displays two essential behaviors: free mode, and virtual surface mode. Free mode is invoked when the cobot's position in its planar workspace is away from all defined virtual surfaces. The cobot should therefore permit any motion that the user attempts to impart. To do this, the steering angle of the wheel is servo-controlled to agree with the measured user forces, allowing to the wheel to roll in whatever direction the user attempts. The behavior is similar to that of a caster wheel on a rolling item of furniture, though there is no physical caster at all.

When the user brings the cobot's position in the plane to a place where a virtual surface is defined, control of the steering angle changes over to virtual surface mode. The wheel is steered such that its rolling direction becomes tangent to the constraint surface, and this tangency is maintained as the user moves the cobot in "virtual contact" with the constraint surface. The user perceives contact with a hard frictionless constraint surface. In practice the illusion is convincing.

Virtual surface mode is ended when the measured user forces are found to be directed away from the constraint surface, at which point free mode resumes.

Figure 2 below shows a "tricycle" cobot with a three-dimensional workspace. Now virtual constraint surfaces can be defined in terms of orientation as well as position within the plane. Three wheels are one too many, and the tricycle cobot can brake by intentionally misaligning its wheels, such that their three axes do not coincide at a common center of rotation. The device can also display the two modes mentioned above: free mode in which the wheels are steered so as to comply with user forces; and virtual surface mode in which the wheels are steered tangent to a software-defined constraint surface, resisting user forces that would violate the virtual surface.

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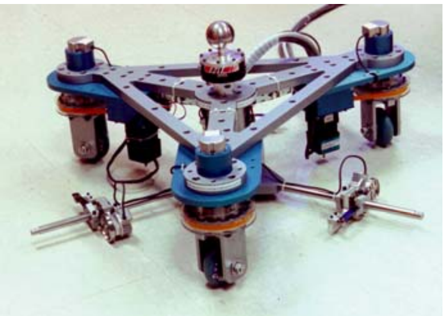


A rolling wheel, which creates a nonholonomic constraint, is essential to the cobots above. Each rolling wheel removes a degree of freedom from the basic mechanism. For instance, the tricycle's three degrees of planar freedom (x, y, θ) are reduced to zero by its three wheels.

In cobots, servo-control is used to selectively add apparent degrees of freedom by steering the wheels, so that (in free mode) the device appears to be unconstrained. In contrast, conventional robots have multiple mechanical degrees of freedom, which may be selectively reduced through servo-control to create apparent surfaces of constraints.

The cobot's low number of mechanical degrees of freedom (zero or one) give it the ability to passively redirect a user's attempted motion. For instance, when a user pushes the unicycle cobot against a virtual surface, the cobot rolls tangent to the constraint surface instead. Since the constraint surface is mechanical in origin, it is inherently strong, stable, and smooth, yet no large motors are involved. A conventional robot defending a constraint surface must actively oppose the user's force using servo-control and motors.

3.

A wheeled cobot for door handling

Figure 3 shows a three-wheeled cobot presently under evaluation at General Motors. The superstructure consists of task-specific tooling for gripping an automobile door. The task is to grip, lift, and remove the door from the vehicle body, which is necessary after painting and prior to assembly of the door and body interior, as these are done on separate lines. The task is difficult because of the tight tolerances, highly curved contours, and complexity of disengaging the door from its hinges and removing it without causing damage to painted surfaces.

The operator guides the cobot to the moving vehicle by pushing and turning the handle. This phase is much like pushing a cart, except that the cobot maintains a constant orientation rather than turning as a cart would in response to steering. Once in close proximity, the cobot takes control of lateral motion as well as orientation, in order to closely approach the vehicle while the operator simply pushes. Lift/disengage is initiated by the operator pressing a button. As the operator continues to push forward, the cobot follows an escape trajectory, which is a virtual surface that brings the door away from the vehicle along a collision-free path. Perceptually, the cobot seems to be guided along this path as if it were in contact with a guiding rail. The cobot then returns translational control to the operator for traversal to the door drop-off station, reorienting itself as the traversal is made so that it is properly oriented for drop off.

The cobot's uncartlike control of its own orientation is at first somewhat disconcerting. However, translational motion occurs as expected for a cart, and an operator requires only moments to learn to move the cobot. It should be noted that turning the handle has no direct physical effect on the cobot except to turn an encoder – the handle is an input device. The cartlike translational behavior is thus purely a software phenomenon; all sorts of strange mappings from measured handle angle into cobot motion are possible.

Wheeled cobots like the door-unloader are very effective at implementing hard, smooth virtual surfaces, and exhibit such low friction in the rolling direction that it is easy for the operator to supply all needed motive power. Indeed the door unloader moves almost effortlessly (5 pounds force) even at its fully loaded weight of over 300 pounds.

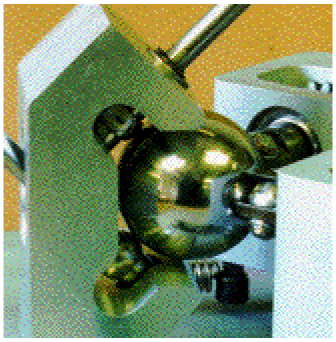
Cobots that don't need a surface to roll upon

Wheeled cobots require a planar surface to roll on, and are suited to tasks which are essentially planar in nature. While there are quite a number of such tasks in automobile assembly and similar plant environments, the requirement of a planar working surface is a significant restriction on the scope of tasks that cobots can address.

Conventional robots have a more versatile architecture, often incorporating (or being entirely) an articulated arm. This versatility requires **revolute** joints, whereas the wheeled cobots above are comprised of **translational** joints. (The motion constraints enforced by the wheels are constraints upon the **translational** motion of the cobot body, so the wheels should be considered translational joints.)

In order to devise a revolute joint we considered carefully the function of the rolling wheel. It is a nonholonomic device which couples a pair of translational velocities Vy and Vx of the wheel's center, constraining them mechanically to a particular ratio $Vy/Vx = \tan(\alpha)$. This ratio is under computer control, via the motor that sets the wheel's steering angle α.

The nonholonomic device analogous to a rolling wheel, but for use as a revolute joint, must couple two angular velocities rather than two translational velocities. It must constrain them mechanically to a particular ratio $\omega_2/\omega_1 = \tan(\alpha)$ where α, which is analogous to a steering angle, is controlled by a computer via a steering motor. This device could for instance be used to couple two consecutive joints of a serial arm, in place of the actuators found at the joints of a conventional robot. Such replacement turns a robot into a cobot.


4.

A suitable nonholonomic device, which is a Continuously Variable Transmission (CVT), is shown in figure 4. The rotation of the two shafts on the left are constrained to be in a proportion dictated by the angle set on the steering rollers on the right. There are many existing CVT designs which permit a continuously variable transmission ratio over a limited range of transmission ratios. Cobots, however, require a CVT with an unlimited range of transmission ratios: in other words we need $\omega_2/\omega_1 = \tan(\alpha)$ for **any** angle α. The CVT shown in figure 6 has this property. Deducing its kinematics from the picture is difficult; interested readers are referred to our other papers.

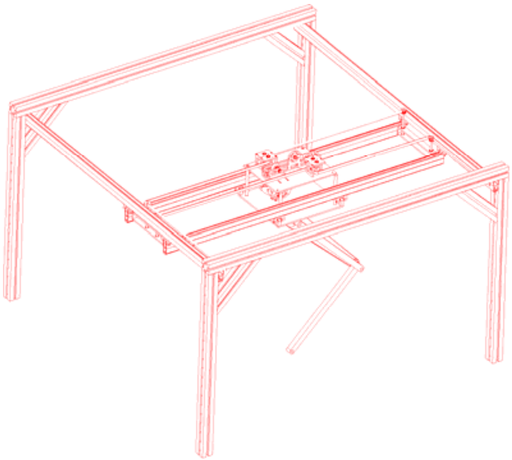
We are currently building a revolute jointed cobot with three CVTs, but our first application of a CVT-based cobot was to a 2d translational cobot, described next.

An x-y gantry-type cobot

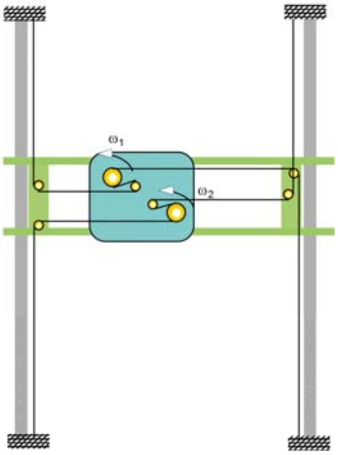
Many manual assist devices are based on overhead rail system. A typical overhead rail system consists of parallel fixed rails, 8 – 20 feet above plant floor, and up to 25 feet apart. Length is unlimited. Riding on these rails are one or two "bridge" rails which span the distance between the fixed rails. A trolley or carriage rides on the bridge rail, and supports either a cable or chain hoist, or a rigid telescoping or articulated arm, at the end of which is task-specific tooling.

The rail system is unpowered and uses low-friction trolleys and bearings. However both friction and inertia are considerable, and furthermore these are anisotropic which makes motion less intuitive. Our objective was to implement virtual surfaces in the rail system's large workspace by making it into a cobot.

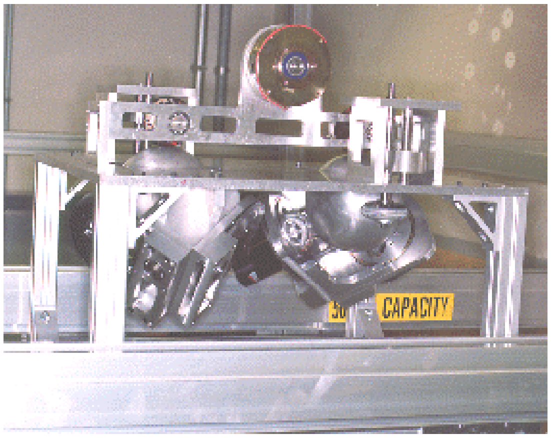
A rail cobot has a 2d translational workspace, in principle just like that of the single-wheeled cobot described above. However in the context of an overhead rail system, a rolling surface is impractical – a cobot wheel would have to roll on an artificial ceiling above the rails. Instead, we used belts as in figure 5b to convert translational motion of the carriage into rotational motions $\omega_1$and ω_2 as shown. (The particular belt arrangement used relates $\omega_1$to one diagonal motion and ω_2 to the other diagonal motion.) A CVT then constrains the ratio ω_1/ω_2 and thus the ratio V_y/V_x, just as a single rolling wheel would constrain them, with the ratio under computer control by servo-steering of the CVT.



5a.



5b



5c

The CVT unit is shown in figure 5c (the spheres are 6 inches in diameter.) We used dual CVTs rather than the minimum requisite single CVT. The CVTs are in "series" – one CVT couples to $\omega_1$while the other couples to ω_2, with a short belt coupling the two CVTs to each other. Thus the ratio ω_1/ω_2 is actually the product of the transmission ratios of the two CVTs individually. Motion of the short coupling belt turns out to be directly related to speed of the cobot endpoint, in whatever direction happens to be the instantaneously allowed direction.

This architecture allows us to add power to the forward direction of motion by driving the short coupling belt. An important observation is that, no matter what the dimensionality of the workspace, the addition of power-assist requires only a single additional CVT, not a doubling of the number of CVTs. Perhaps even more importantly, the addition of power-assist requires only a single motor.

In the power-assist overhead rail cobot, a small 200 watt motor amplifies the operator's applied force in the forward direction. This motor is adequate to overcome the inherent friction of the rail system and belts, and to considerably ease the human effort required to bring a 150kg payload from rest to a speed of several meters per second.

For safety reasons one would not want a motor of greater than human power. By comparison, if our virtual walls relied for their strength on motors rather than CVTs, turning the payload through a 90 degree bend with a turning radius of 30cm, when it is travelling at 2 m/s, would require a 4,000 watt motor. An advantage of the cobot architecture is that the strength of the virtual surfaces ultimately depends on mechanical elements, not on high power motors. This confers a degree of safety, and is responsible for the hardness and smoothness of the perceived virtual surfaces. The addition of a low-power motor to assist in forward motion does not remove this advantage.

The rail cobot is presently under evaluation at Ford Motor Company.

In materials handling applications such as automobile assembly, even the simplest haptic effect – free mode – can be very useful. In free mode the cobot gives the operator the perception that the payload is responding in an unconstrained and natural way to his applied forces. This is actually a *simulated* lack of constraint, and the existence of a computer in the loop gives an opportunity for many improvements over the natural behavior of the payload: virtual haptic effects. For instance the lack of isotropy of the underlying kinematic mechanism, e.g. an overhead rail system or an articulated arm, can be masked by the cobot in free mode so that the payload responds in a more predictable way to the operator's intentions. Or the inertia of the payload – its reluctance to change its direction of motion – can be masked so that it is perceived as lighter and more maneuverable than it actually is.

Research areas

Building and controlling cobots has exposed many fascinating research areas. Many research topics that have been explored in robotics suggest new and different questions in the context of cobots or of haptic display generally. A sampling includes:

- Path planning – In robotics creating the appropriate motion trajectory for a given task is a current issue. In cobots the corresponding problem is to create the virtual surfaces which bound and guide the motion of a payload controlled by a human operator, in support of a given task.
- Haptic effects – Free mode and virtual surface mode are but two poles of a unlimited range of haptic effects which can be invented. For instance, a virtual surface may have a “penetration strength” beyond which it gives way, or it may have a simulated attractive potential field, or it may yield compliantly to operator pressure against it.
- High dimensions – For cobots with workspace dimension greater than two, virtual surfaces can exist with a variety of dimensionalities (“surface” remains the generic term). Describing these surfaces efficiently and usefully is non-trivial.
- Control – Novel control issues are created by the essential role of the human operator in the motion of a cobot. For instance, a robot trajectory is a path through space parameterized by time. In cobot control, progress along a path may be entirely at the discretion of the human operator, who may stop or even reverse direction along a path. The utility of a time as a parameter is thus greatly reduced, yet control software must maintain the cobot on the path.

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