

Feature

Cobots

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Abstract

Collaborative robots – “cobots” – are intended for direct interaction with a human worker, handling a shared payload. They are a marked departure from autonomous industrial robots which must be isolated from people for safety reasons. Cobots are also distinct from teleoperators, in which a human operator controls a robot and payload remotely. Cobots interact with people by producing software-defined “virtual surfaces” which constrain and guide the motion of the shared payload, but add little or no power. Ergonomic as well as productivity benefits result from combining the strength and computer-interface of the cobot with the sensing and dexterity of the human worker. This paper explains cobots as one approach to an emerging class of materials handling equipment called Intelligent Assist Devices (IADs). We describe two cobots of this class presently in industrial testbed settings. Future applications of cobots’ virtual surfaces are tool guidance in image guided surgery, and haptic display in which the surfaces of a CAD model can be felt.

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Introduction

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Cobots interact with people by producing software-defined “virtual surfaces” which constrain and guide the motion of the shared payload, but add little or no power. Ergonomic as well as productivity benefits result from combining the strength and computer-interface of the cobot with the sensing and dexterity of the human worker.

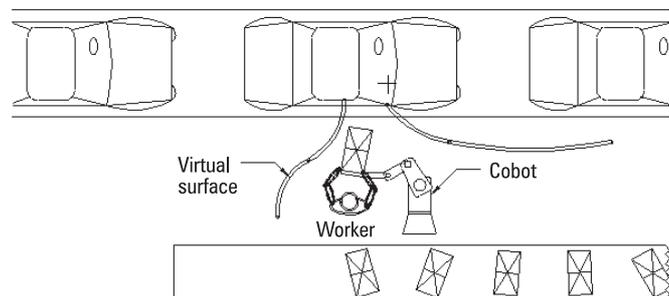
This paper explains cobots as one approach to an emerging class of materials handling equipment called Intelligent Assist Devices (IADs). We describe two cobots of this class presently in industrial testbed settings. Future applications of cobots’ virtual surfaces are tool guidance in image guided surgery, and haptic display in which the surfaces of a CAD model can be felt.

In 1995 Northwestern University and General Motors Corporation initiated a project in the emerging area of Intelligent Assist Devices (IADs) (Akella, 1999a). IADs are intended to improve ergonomic working conditions, product quality, and productivity through an appropriate combination of robotic technology with traditional Manual Assist Devices (manually powered overhead rail systems, jib cranes, etc.).

Our particular approach to IADs was to seek a way of implementing virtual surfaces, which we proposed as a primary form of interface between human worker and computer in material handling tasks. Virtual surfaces may be understood by analogy to the role of a straightedge in drafting. Creating a straight line freehand is a task that most people perform slowly and poorly. With the help of a straightedge, however, the task is done better and quicker. Virtual surfaces are a generalization of the straightedge: they provide physical guidance, in as many

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Figure 1 A cobot and a human worker work together, with the cobot providing computer-generated “virtual surfaces” that the worker can make use of in maneuvering a payload accurately into the door opening of a car on an assembly line



dimensions as necessary and along any shape path.

Our invention of cobots early in the project gave us a general and programmable means of setting up large-scale virtual surfaces. When a human worker pushes a payload up against a virtual surface, 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, worker and payload motion is unconstrained (“free mode”).

Conventional (servomotor-based) robots could in principle also be used to set up virtual surfaces. Doing so, however, requires that the robot's joint motors be strong enough to resist the worker's pushing forces and the payload's inertial forces that would penetrate a virtual surface. Such powerful motors pose safety problems. Also, in practice, the performance of such virtual surfaces (e.g. their smoothness) has proven to be poor. Cobots, by comparison, employ joints which mechanically provide constraint. The constraint is continuously adjusted under computer control, making it possible for the computer to establish arbitrarily complex virtual surfaces. Virtual surfaces established by cobots are intrinsically smooth, and do not require powerful motors to defend them.

Impact in materials handling

Ergonomic problems in material handling have been widely recognized in recent years. Repetitive motions, excessive loads, awkward postures and vibration can all lead to cumulative trauma disorders such as carpal tunnel syndrome, tennis elbow, and lower back pain,

any of which can incapacitate a worker for days to weeks. Cobots can address ergonomics concerns, and provide productivity benefits as well:

- *Ergonomics*: virtual surfaces produced by cobots can guide worker and payload motion, minimizing the need for the worker to exert lateral or stabilizing forces on a payload. Lateral and stabilizing forces use the muscles of the upper body and back, which are susceptible to injury. Motive forces use principally the large muscle groups of the lower body, with less risk of injury. Thus we believe that providing mechanical guidance may often be of greater ergonomic benefit than providing mechanical power.
- *Navigation and inertia management*: cobots can assist in the maneuvering of large, unwieldy objects, especially where complicated motions or tight tolerances are necessary. In particular it is important to realize that the virtual surfaces provided by cobots are meant to be used intentionally by the human worker. They are fixtures to be exploited, not barriers to be avoided.
- *Workspace isotropy (avoiding rail awkwardness)*: heavy assemblies supported by the very common passive overhead Cartesian rail systems are often much easier to move along one translational axis than the other. This non-uniformity of workspace leads to awkward movements. Cobots mask the non-uniformity so that the payload's behavior seems intuitive to the worker. We have built such a “rail cobot”, currently located at Ford Motor Company Advanced Manufacturing Technology Division (AMTD).
- *Obstacle avoidance*: virtual surfaces can be set up to surround and protect obstacles in the workspace, effectively steering the payload around them and preventing collision.
- *Software-driven material handling*: cobots can, via interface to a computer, guide an operator in the correct selection of pickup and placement locations as well as path. As all aspects of the business world undergo computerization, cobots can provide a computer interface to materials handling systems that must, for a variety of reasons, continue to use the special skills of human workers.

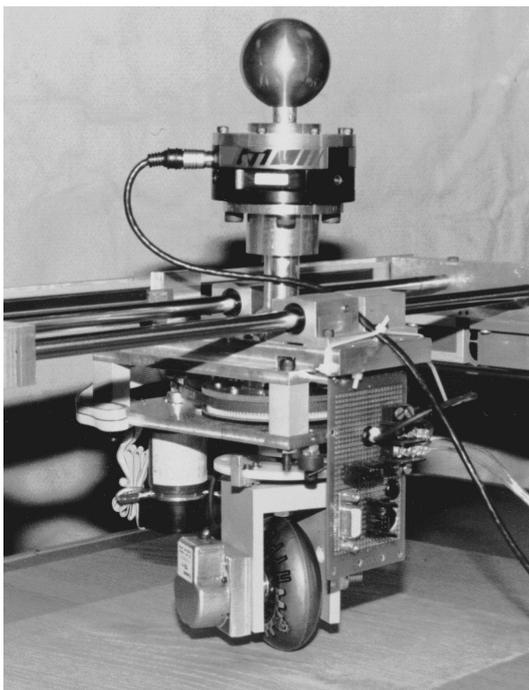
- Productivity: by exploiting virtual surfaces, operators can make quicker and surer movements.

How cobots use transmissions to create virtual surfaces – example: the “unicycle” cobot

Cobots implement virtual surfaces by using transmissions. This avoids the need for brakes or other dissipative elements, which necessarily absorb energy of motion and thus do not provide a frictionless virtual surface. Transmissions are energetically neutral. A rolling wheel is the simplest example of a transmission, and may be used to illustrate a simple cobot. This is little more than a single wheel in contact with a flat rolling surface, as shown in the Figure. It has a two-dimensional Cartesian (x - y) taskspace, parallel to the rolling surface. Using this model we will discuss two essential behaviors of a cobot: virtual surface mode, and free mode.

The interface to the human operator is a handle, shown just above a force sensor (Figure 2) which is able to measure the x - y forces applied by the operator. If there were a payload, it would be below the force sensor so

Figure 2 The simplest cobot is little more than a free-rolling wheel. By active control of the wheel’s rolling direction, a control computer can confine the user’s handle to follow a virtual path or surface. In “free mode” the computer can allow the operator to move the device about freely, by steering the wheel to comply with the operator’s wishes transparently



Source: Wannasuphprasit (1998)

that operator-generated forces could be distinguished from inertial forces of the payload.

The wheel is free to turn on its axle. There is no motor to drive its rolling motion. The wheel is held vertical by a shaft whose axis is coincident with the point of contact between wheel and rolling surface, i.e. there is no “caster” of the wheel. The wheel has a steering angle β_s defined as the angle of its rolling direction from the x axis. This angle is measured by a rotational encoder. Control of the steering angular velocity ω_s is accomplished by a conventional velocity controller, which takes ω_s as input. Owing to the absence of caster, action of the steering motor cannot cause taskspace motion, and forces applied to the handle do not create a torque on the steering motor. Thus there is a decoupling of taskspace motion from steering action.

Also shown in the Figure is a rail system which serves to keep the cobot upright and restrict it to its two-dimensional Cartesian taskspace. The rail system is instrumented with translational encoders to measure the position of the cobot within its taskspace. Another rotational encoder monitors the rolling speed of the wheel, \mathbf{u} .

This cobot, nicknamed Unicycle, is mechanically well equipped to implement virtual surfaces. In its two-dimensional taskspace, a virtual surface is a curve in the plane, $\mathbf{p}(s)$, where s is path length along the curve and \mathbf{p} is a 2-vector in the plane. Let us suppose we wish this to be a bilateral surface to which the cobot is to be confined, which we will call path mode. In the next section we will address its unrestricted motion when it is not in contact with a virtual surface, free mode. A unilateral virtual surface is accomplished by a simple software switch between free mode and path mode, based on whether the user’s applied force is directed toward the free side or the prohibited side of the virtual surface.

In the absence of errors, confining the cobot’s motion to a curve in the plane requires that we measure the cobot’s position s along the curve, and maintain its steering angle β_s such that its rolling direction is tangent to the curve at that location. Thus open-loop control for a cobot path-tracking a virtual surface may be accomplished by $\omega_s = \mathbf{u}/\rho$ where \mathbf{u} is the measured rolling speed of the wheel, ρ is the instantaneous radius of curvature of the virtual surface, and ω_s is the

commanded steering angular velocity. Closed loop control is addressed in Colgate (1996).

The resulting virtual surface relies for its strength and hardness not on actuators, but on the properties of a rolling wheel. The wheel rolls freely despite large perpendicular (“skidding”) loads, thus providing a low-friction virtual surface. In practice we use Rollerblade® wheels, taking advantage of a technology that has been optimized for a sport requiring similar wheel properties. Virtual surface strength well over 100 lbs is attainable. Perceptually, the virtual surface can be easily confused with a well-greased rail, confining motion to any programmed curve in the plane.

Free mode is implemented by a servo loop in which the operator’s applied force is measured by a force sensor, and the cobot’s single degree of freedom is steered to allow motion in the direction that the operator’s force directs. To make the cobot feel like a free mass, steering speed is inversely proportional to rolling speed; thus when moving quickly more user force is needed to turn. Since any sort of software filter may be applied to the operator’s force, we are afforded the opportunity for a great variety of haptic effects.

An industrial materials handling cobot

Moving from the Unicycle cobot’s two-dimensional workspace (xy) to a three-dimensional planar workspace ($xy\theta$) requires a general theory of multidimensional cobot control (Gillespie, 1999). We built an $xy\theta$ “tricycle” cobot, with the help of which multidimensional cobot control was developed, while GM built an industrial version, pictured in Figures 3 and 4.

With three wheels, virtual constraint surfaces can be defined in terms of orientation as well as position within the plane. Kinematically, three wheels are one too many, and the tricycle cobots can brake by intentionally misaligning their wheels, such that their three rolling axes do not coincide at a common center of rotation. They can also display the modes mentioned above: free mode in which the wheels are steered so as to comply with user forces; path mode in which the cobot steers along a defined path through 3-space, 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.

Figure 3 Graduate student Witaya Wannasuphprasit with a prototype “tricycle” cobot capable of defending virtual surfaces in three-dimensions (x , y , and orientation θ). A virtual surface (on screen) corresponds to the table edge



Figure 4 General Motors’ door-unloader cobot provides virtual surfaces which assure that the door does not collide with the car body, and which assists in several other aspects of the task. Yet the worker retains direct control of the payload as well



Source: Akella (1999b)

A rolling wheel, which creates a nonholonomic constraint, is essential to the cobots pictured. 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. In practice it is quite difficult for robots to produce convincing virtual surfaces, but this is the intrinsic mode of cobots.

Benefiting from our experience in designing and programming the tricycle cobot, GM's cobot is a rugged yet highly maneuverable device. It assists in removing doors from newly painted auto bodies prior to assembly of the cabin. This task was chosen because it was difficult for workers to remove the doors manually without marring the surfaces: the curvature and styling of the body panels is such that a specific "escape trajectory" is needed to remove the door safely. Human versatility and dexterity are still very important in other phases of the task; this is not a task that ought to be fully automated.

The door-unloader cobot glides easily on pairs of servo-steered Rollerblade™ wheels with only a few lbs of operator force. During some task phases the operator controls position while the cobot controls orientation, aligning itself to the car body or to the door rack across the walkway as appropriate. In close-approach phase a virtual surface is created close to the vehicle's rocker panel, guiding the cobot to the correct location to grip the door without colliding with the vehicle. The "escape trajectory" is executed in path mode. When crossing the walkway the cobot is in free mode, giving the operator direct and intuitive control over both translation and orientation.

Cobots for other applications

Haptic rendering

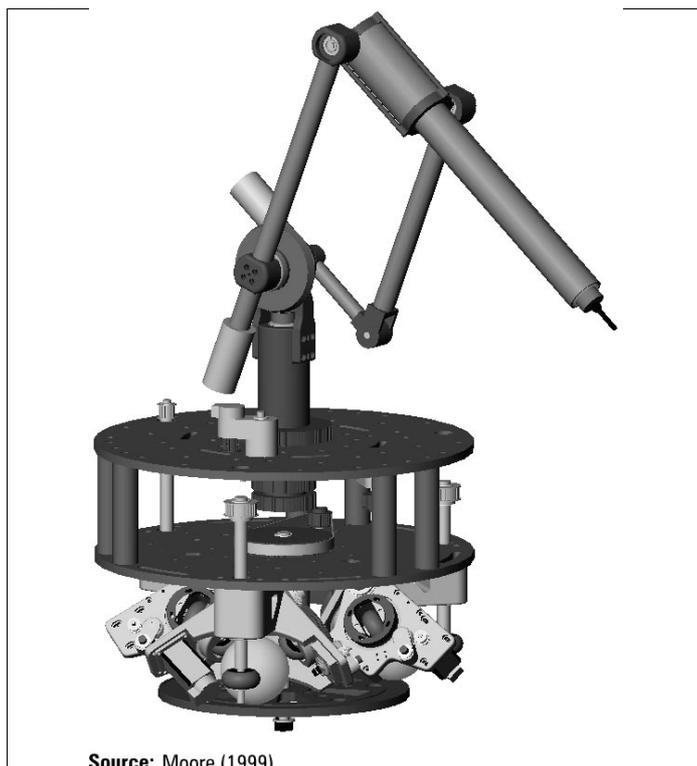
In the past decade, haptics has grown from an unknown field to a widely recognized discipline with both scientific and commercial significance. Applications of haptics may be found in entertainment, computer interface, image guided surgery, training and rehabilitation, and

computer aided design (CAD). Haptic rendering is analogous to "graphical rendering", referring to high-quality "touchable" representation of computer-generated surfaces.

As an example, consider the carved clay models used in conjunction with CAD models in designing automobile bodies. Both time and information are lost in converting between the two forms. Direct haptic exploration of CAD models is desired, but the state of haptic rendering using conventional servo-actuated haptic displays is not yet advanced enough to rival the sensitivity of physical touch.

Cobots may provide a superior technology for the haptic display of complex surfaces. Cobots use a different physical principle to display surfaces, relying on the mechanical properties of a continuously variable transmission (CVT) as the basis of virtual surfaces, rather than on powered servomotors. The CVT serves the same function in haptic-display cobots as does the rolling wheel in the unicycle and tricycle cobots described above. The CVT makes it possible to build cobots having the familiar "armlike" design of many robots. Figure 5 shows how CVTs make

Figure 5 A cobot with the familiar workspace of a robotic "arm". The intended use is haptic display of virtual surfaces based on CAD solid models, so that a user can feel the surfaces of the object or parts designed. Such cobots require revolute joints rather than rolling wheels as in the cobots shown in Figures 3 and 4. For this purpose they use the CVT shown in Figure 6



Source: Moore (1999)

possible the revolute joints needed for “arm-like” cobots. We are presently building a cobot (Figure 5) for haptic display, having a workspace similar to full human armspan.

Image guided surgery

In this application safety is essential, and a cobot’s ability to guide motion without possessing a corresponding ability to move on its own can totally remove concern about some failure modes. Perhaps more importantly, the quality of a virtual surface enforced by a cobot originates in its physical mechanism, rather than in servo-controlled actuators, thus yielding harder and smoother surfaces than can be achieved by a robot. Preserving the critical sense of touch in surgery requires high quality “shared control” between surgeon and robot, for which smoothness of motion is essential.

Rehabilitation and exercise

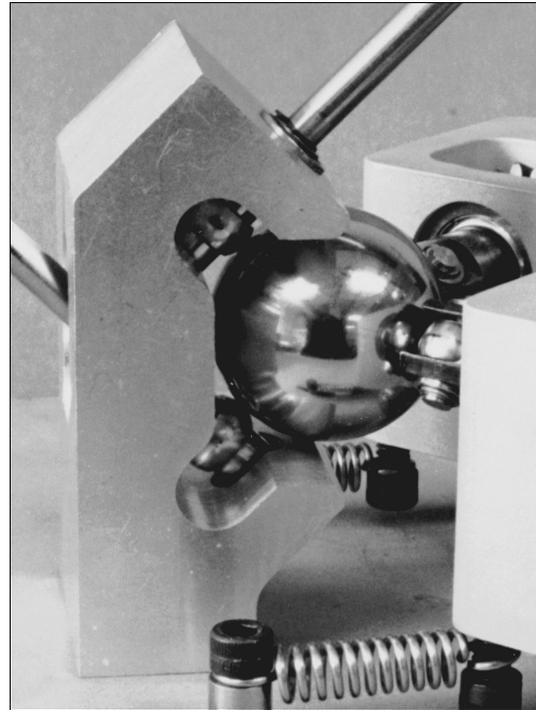
Popular weight training equipment, originally designed for rehabilitation, uses shaped cams and other mechanical components to confine a user’s limb or body motion to a particular trajectory. While these trajectories are somewhat adjustable, far greater versatility could be achieved if the motion trajectories were encoded in software rather than frozen into the mechanical design of the equipment. Cobots can enforce virtual trajectories with the smoothness, hardness, and safety required for this application.

Continuously variable transmission for revolute-jointed cobots

The rolling wheel in the planar cobots may be thought of as a translational transmission element. A transmission holds one velocity or angular velocity in proportion to another. The rolling wheel may be thought of as a device which relates the x translational velocity of a certain point of a body to its y translational velocity, and holds those velocities in proportion. The proportion is adjustable by steering the wheel: we have $v_y/v_x = \tan \beta_s$, where β_s is the steering angle of the wheel. Thus a steerable passive rolling wheel formally falls in the class of kinematic mechanisms known as continuously variable transmissions, or CVTs (Figure 6).

For cobot architectures with revolute joints, the wheel (as a CVT) is replaced by a device which holds two angular velocities in proportion, with the ratio between them being “steerable” under computer control. There

Figure 6 First prototype of a CVT which makes possible revolute-jointed (“armlike”) cobots. The internal workings of more practical versions of the CVT are less visible



are a great number of CVT designs that hold two angular velocities in proportion, with $\omega_1/\omega_2 = c$. We will express the transmission ratio c as the tangent of an angle β_s to maintain an analogy to the rolling wheel. Just as for the rolling wheel, for use in a cobot we require the ability to rotate the transmission angle β_s without limit, through multiple revolutions. We have developed a rotational CVT with this behavior. Our first prototype is shown above: the angular velocities of the rollers on the left of the central sphere are held in a ratio determined by the angle of the rollers on the right. Understanding its kinematics from a photo is nearly impossible. The kinematics of this mechanism are described in detail in Peshkin (1996).

CVTs have emerged as a crucial element of cobots. Strong, compact, and easily assembled designs are needed. We have initiated a study of the contact mechanics of CVTs, which impacts torque-handling capacity, slip, and wear. We have also initiated a program in CVT design.

Conclusions

Cobots hold great promise for human-computer physical interaction. The philosophy

behind cobots is that shared control of motion, rather than amplification of human power, is the appropriate metaphor for collaboration. Benefits may be expected in ergonomics, in productivity, and in the interface of computers and information systems to those many activities which continue to make good use of uniquely human skills.

Readers who wish to learn more about cobots may wish to consult the articles mentioned in the references. Written material of both greater and lesser technical detail may be found at the cobot Web site, accessible via the URL <http://cobot.com>. We have founded a company for the commercialization of cobot technology, Collaborative Motion Control (“CoMoCo”) Inc., which is also reachable at the above URL. Some intellectual property rights in cobots are held by Northwestern University.

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