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New intelligent power-assist systems based on differential transmission

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SUMMARY
This paper presents a novel Cobotic system with differential CVT. The new system is significantly cheaper, simpler to control and more efficient than Cobots with S-CVTs. Both path-guidance and power-assist functions can be simply realized with the new system. Basic structures, kinematic and dynamic models, as well as control algorithms, which are essential for design, control synthesis and control of the system, are briefly presented in the paper.

KEYWORDS: Intelligent power assist; Cobot; Differential CVT; Interaction control.

1. INTRODUCTION

Recently, issues of productivity and ergonomics have increasingly motivated producers and end-users of material handling equipment to qualitatively improve devices and systems. Although conventional material handling devices (generally referred to as "assist devices," including articulated arms, balancers, hoists, jib cranes, etc.) have a positive impact in terms of ergonomics, they are limited when considering efficiency, precision and safety. During the last decade, there has been considerable effort in research and development to address the automation of manual assembly, as well as other material handling processes, through the use of manipulation robots. In spite of the advances already achieved, however, only specific robotic applications have been established, usually for the mass production of relatively simple parts. Further automation through the use of industrial robots is impeded by one or more fundamental limitations, such as: high costs, still restricted and/or expensive adaptation to unstructured variable environments, complex programming (which requires educated personnel), insufficient availability, changeable and shrinking production, etc.

A second crucial problem of conventional material handling equipment concerns work related health issues. Fatigue, stress and musculoskeletal disorders (MSD) of the operator are detrimental effects resulting from the devices' lack of responsive reaction and management of payload inertia. Work-related low back disorders are a significant and increasing problem worldwide. Surprisingly, this is a common occurrence in the leading industrial countries (USA and Europe). According to reports from the European Agencies for Safety and Health at Work (OSHA), about 30% of European workers suffer from back-pains which are mainly caused by high physical demands (i.e. the lifting and manual handling of loads), repetitive movements, awkward postures, etc. Back pain is a problem that causes enormous social, health and economic costs, which are estimated to range from 2.6 to 3.8% of the Gross National Product (GNP) for member states.

There is increasing recognition that a more effective and integrated "holistic" approach is urgently needed to solve the above-mentioned problems. The development of sophisticated material handling equipment plays a key role in this approach. In the USA and Japan, a significant step forward has been achieved during the last decade by establishing a new framework for material handling equipment. This new generation of ergonomic assist devices, are also known as "intelligent assist devices" (IAD), collaborative robots (cobots), holonomic manipulators, etc. These devices use a computer control which improves movement of heavy items and responds precisely to the operators' wishes. The IADs share some of the same characteristics with the conventional assist devices and with the industrial robots. They help human workers instead of replacing them. By using IADs, the operator can optimally co-ordinate and control motion while utilizing unmatched sensing, intelligence, experience and skills.

This paper presents a novel Intelligent Power Assist Device (IPAD) that integrates power assistance, motion guidance functionalism, an advanced interaction control and programming algorithms into a reliable, efficient and ergonomic material handling system. This new IPAD, which is being developed at FhG-IPK, belongs to the novel class of systems within the framework of an emerging technology of powered equipments that combine the features and benefits of industrial robots with that of handling devices for the direct co-manipulation by a human operator (Figure 1). Compared to the industrial prototypes, they are advantageous in regards to cost, inertia management and force application performance. The new IPAD will also integrate sophisticated force-feedback and programming (skill-learning) functions, as well as compliant motion guidance ("compliant virtual walls") and semi-autonomous functions (e.g. "homing", "pressing," etc.).

2. REVIEW OF EXISTING IADs

The conventional assist devices available on the market are commonly used to balance weight and for grasping and rotating parts. These systems do not include computer control and are considerably cheaper and easier to operate

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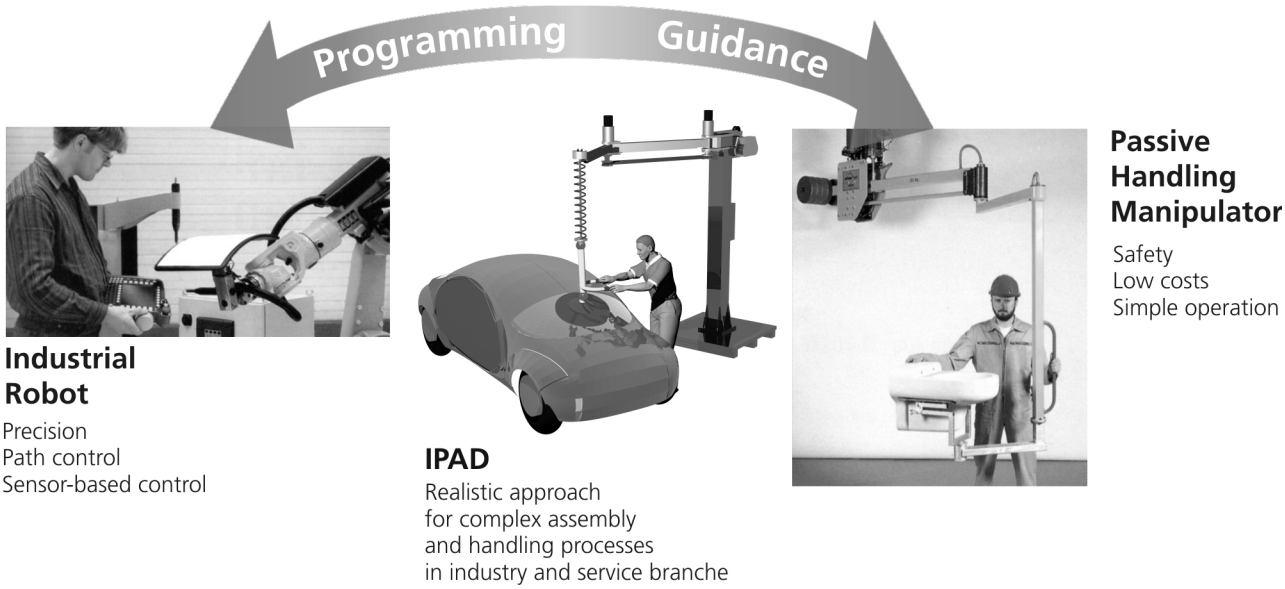


Fig. 1. IPAD – A reliable approach for advanced material handling.

than industrial robots. However, for applications that require rapid and accurate movements, they are slow, awkward, not responsive and difficult to coordinate. These problems are not only critical for the time-demanding assembly tasks (such as in the automotive industry) but also for the simple transport of bulky parts. The high physical exertion that is involved in using these devices, while pushing and pulling in an awkward posture is often the cause of the health problems described above.

In order to overcome these problems, a new concept of IAD has been conceived at Northwestern University and Berkeley[1–3] on the initiative and funding from automotive industry and OSHA. Kazerooni[1] has developed the concept of "human extender" and "power amplifier" in which a robot amplifies the operator's efforts to lift and manipulate parts. Colgate and Peshkin[2,3] have established the concept of "collaborative robot" – Cobot – providing programmable motion guidance. The cobot's main function is to realize a "virtual guiding surface" along which the part can be manoeuvred and positioned. The cobot provides a physically passive, and consequently safe and stable device. The computer control is applied to redirect the operator's force, rather than to produce the motion. The essential cobot element is the *continuous variable transmission* (CVT) which allows the control of relative motions among device joints. Colgate and Peshkin utilise a sphere caged by four rollers (so-called *spherical* or *S-CVT*, USA Pat. Nr. 2,727,396 from 1951), which allows a smooth adjustment of the transmission ratio. A similar system has been applied by Nakamura.[4] At Georgia-Tech University, Book et al.[5] have applied brakes on each joint to realize a passive trajectory-enhancing robot (PTER).

Based on the above developments and intensive research (in the USA the funding for IAD projects averaged up from 500 k$ in 1998 to 2500 k$ in 1999), the first products have recently appeared on the market, such as Zimmerman's Z-Lift and Goerbel's G-force (based on Kazerooni's vertical amplifier); iTrolley, iLift and RailCobot from Cobotics Inc. meant to implement cobotic technology (USA Pat. 5,952,796); Fanuc's IAD (USA Pat. 6,204,620) based on a power assisting rail robot; Positech's PowerTouch developed in cooperation with the University of Iowa, etc. These pilot products were successfully tested foremost in the automotive industry (at GM and Ford premises) and clearly demonstrated increased ergonomic and productivity benefits. A draft of IAD ANSI standards is currently being created in the USA.

In Europe, interest for this emerging technology can unfortunately be estimated as negligible in comparison to the development in the USA, in spite of a world leading automotive industry and an extensive production of material handling and robotic devices. Delnondedieu and Trocazz[6] have built "a passive arm with dynamic constraints" (PADyC) utilizing freewheels in each passive joint to constrain the motion. The system was developed as a passive instrument carrier for cardiac puncturing.

3. NOVEL IPAD COMBINING POWER-ASSIST AND MOTION GUIDANCE FUNCTIONS

Based on the initial experience with new IADs, it is widely recognized that a significant improvement of this novel technology can be reached by combining power-assist with motion guidance functions. The power-assist robots commonly provide the interface with the human operator via a force sensor (e.g. human enhancers, admittance displays, etc.) and dramatically reduce efforts needed to manoeuvre the manipulator. However, safety is a critical problem since they possess high power and can potentially injure the operator. The pure motion guiding systems are intrinsically passive and safe; however, they do not provide the inertia management and force amplification that is highly necessary for manoeuvring heavy parts. Therefore, an ideal cooperating material handling system would combine the *passive motion guidance* with *a limited power-assist* which would be enough to compensate for frictional and acceleration/deceleration forces and yet not enough to wound the operator.

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A concept for transferring a limited power using S-CVT has also been recently established.[7] However, force and power transmission are quite constrained and expensive in S-CVT. Moreover, S-CVT exhibits non-linear dynamic behaviour that is difficult to control.[8] Therefore, at Fraunhofer-IPK a new IPAD system has been developed utilizing the CVT principle based on modified differential gears that are more suitable for power transmission and control.

3.1. Differential gear based CVT

Recently, CVTs technology is becoming rather attractive because of a growing interest within the automotive industry to develop a new generation of engine transmissions that increase efficiency, fuel economy and safety. Although there are different CVT principles, the most applied concept is based on variators with adjustable working diameters of the two main pulleys. These CVTs can meet reliable torque/speed requirements; however, they are heavy and expensive for applications in material handling systems. A simple and promising CVT has been designed at IPK based on differential gear mechanisms (Figure 2). The differential gears are commonly applied in automotive systems to split the input engine torque two ways, allowing each output to spin at different speeds. However, the differential possesses two degrees of freedom (DOFs), and can also be applied to adjust transmission ratios between one of the two inputs, e.g. *ring-gear* $\omega_r = \dot{q}_r$ (Figure 2), and the output, e.g. *carrier* $\omega = \dot{q}$, by controlling the speed of the second input, in the considered case it is sun gear (Figure 2) connected to the drive $\omega_d = \dot{q}_d$. Taking into account that $q = q(q_d, q_r)$, the relationship between angular velocities for the considered gear (Figure 2) is defined by

$$\dot{q} = \frac{\partial q}{\partial q_d}\dot{q}_d + \frac{\partial q}{\partial q_r}\dot{q}_r = k\dot{q}_d + (1-k)\,\dot{q}_r \tag{1}$$

where k is so-called *stationary transmission ratio* characterizing the differential train performance, obtained for fixed ring gear (in this case the differential becomes a hypocyclic planetary gear)

$$k = k_{\dot{q}_r = 0} = \frac{\omega - \omega}{\omega_d - \omega_r} \tag{2}$$

Commonly in speed reduction gears is $k \ll 1$. The angular velocities relationship can be written as

$$\omega_d = \bar{k}\omega + (1-\bar{k})\,\omega_r \tag{3}$$

where $\bar{k} = 1/k$. For $k - 1$ and $\omega_d \gg \omega_r$, the equation (1) becomes $\omega \approx k\omega_d + \omega_r$ i.e.

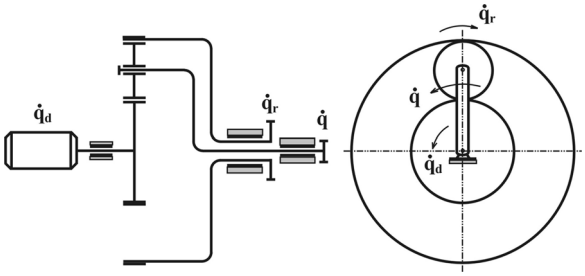


Fig. 2. Elemental hypocyclic differential gear.

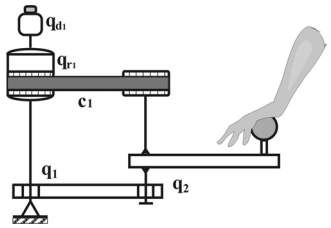


Fig. 3. Basic serial configuration.

$$i = \frac{\omega}{\omega_r} \approx \frac{k\omega_d}{\omega_r} + 1 \tag{4}$$

Obviously, if one realizes the rotation ω_r, it is possible to regulate the above transmission ratio by measuring ω_r and controlling drive velocity ω_d.

3.2. Kinematic structures of IPAD with differential CVT

This section discusses the use of differential CVT in novel power assist systems. The elemental mechanical configuration corresponding to an IPAD with a configuration, referred to as *serial structure,* is presented in (Figure 3). This system consists of a SCARA-like manipulator with two links. The first joint is connected to the output of a differential train. The second joint is via a teeth-belt (with the transmission ratio c_1) connected to the ring-gear of the differential. Thus by closing an additional internal coupling chain between manipulator joints, the basic so-called "cobotic" structure is realized. The internal chain allows controlling the relationship between rates of change $\Delta q_1/\Delta q_2$. Indeed, the system is underactuated, since only q_{d_1} is driven. Commonly, the friction in the system arrests the ring-gear (and thus the joint q_2) reducing DOFs to one. Then, the drive system can only move the first joint, causing both links to rotate as one body around this joint.

That represents the main potential drawback of the considered system compared to the holonomic cobots with S-CVT. The transmission ratio is in S-CVT controlled by position of the steering-drive (pulley), which cannot bring the system into motion. The manipulator remains standing still, until the operator begins to move it. Hence, cobots with S-CVT are intrinsically passive and safe systems.

On the other hand, the differential gear regulates the transmission ratio via angular velocity, which means a mistake could cause the system to move, in spite of the operator's wishes to do so. However, contrary to the industrial robotic systems, an erroneous motion in the new IPAD appears not to be critical. As mentioned above, the role of the drive system in (Figure 3) is to regulate the transmission ratio between manipulator joints, rather than to move the system. Consequently, the power of the drive system is significantly lower than in industrial robots, and the risk of injury or environmental damage is negligible. Moreover, the possibility of the drive and differential CVT to bring/transmit a limited power to the system is essential for realizing the *power-assist* (e.g. inertia managing) functions.

The basic serial system in (Figure 3) possesses only one drive and is mainly intended to realize *path guidance*

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functions. The system's functional principle is described as follows. Similar to the conventional handling devices, the human operator moves the system via an appropriate interface on the manipulator tip (see Figure 3), which causes the second joint to rotate. If the drive (i.e. control) is inactive, then this rotation is transmitted via teeth-belt (which is connected to the ring-gear) and the differential gear according to equation (4). In this case, both joints are connected with a fixed transmission ratio, which causes the system to move like a mechanism with one DOF along a fixed path. By activating the control system, it is then possible to control the motion transmission ratio $r_{12} = \Delta q_1 / \Delta q_2$ based on the measured rate of change Δq_2 produced by the operator. By these means, a programmable nominal trajectory can be realized in the manipulator's workspace. According to the principle "human moves – machine directs" the operator realizes the main motion. In order to prevent an undesired system motion after the goal position has been achieved, it is necessary to apply conventional and reliable elements such as brakes, clutches etc. It is worth mentioning here that the new IPAD generally does not require a force sensor (like an admittance display). The operator's action is sensed by using a simple position sensor within joints.

Figure 4 presents a five-bar mechanism version of a serial system IPAD, in which the axes are coupled to one another by one differential CVT. A characteristic of this system is that the operator acts on both joints through a mechanical interface (mechanism link).

A basic two-link system with so-called *parallel structure* is presented in (Figure 5). This system includes an additional differential drive system connected to the second joint. As will be demonstrated in the next section, this system permits the realization of both *path-guidance* and *power-assist* functions. The parallel structure also allows various operating modes. If the common ring shafts are fixed, the system works as a conventional robot (with limited power). If the drives are fixed, the mechanism is passive and can be moved by the human along a trajectory defined by kinematic parameters and gear ratios. In the *cobotic mode*, both drives are servo controlled and the realized motion depends on drive torques and force exerted by the operator.

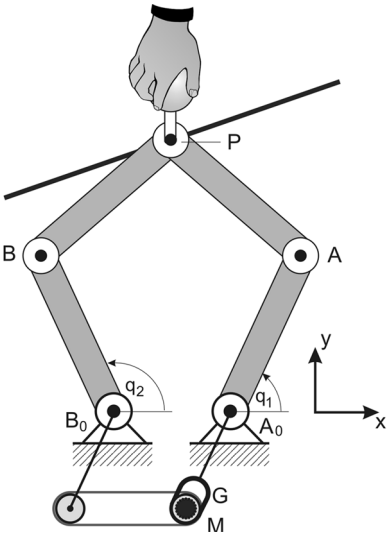


Fig. 4. Five-bar serial configuration.

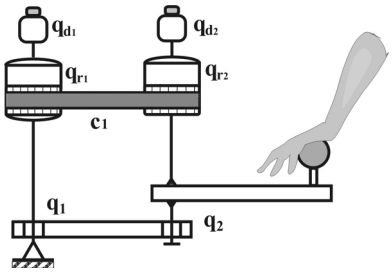


Fig. 5. Basic parallel configuration.

4. SYSTEM MODELLING

Models of kinematics and dynamics are essential for proper design, path planning and control synthesis of a new IPAD. As already mentioned, the dynamics of cobotic systems with holonomic S-CVT is rather complex to model. In spite of the several possibilities for power flow in the differential gear trains, as well as the uncertain mechanical efficiency, the system with differential CVTs are considerably easier than S-CVT cobots[8] to model. This section briefly presents background models of the new IPADs which are based on differential gear trains.

The dynamics of a basic differential CVT can be described by the following equations for power flow and kinematic constraints

$$\begin{aligned} &\delta q_d \eta_n (\tau_{cd} - J_d \ddot{q}_d - b_d \dot{q}_d) + \eta_r \delta q_r (\tau_r - J_r \ddot{q}_r - b_r \dot{q}_r) \\ &\quad - \delta q (\tau + J\ddot{q} + b\dot{q}) = 0 \\ &\delta q = k \delta q_d + (1-k)\, \delta q_r \end{aligned} \tag{6}$$

where J_d, J_r and J are equivalent drive, carrier and ring gear moments of inertia respectively, b_d, b_r and b corresponding damping coefficients, τ_r and τ are input and output torque on ring-gear and carrier, respectively, τ_{cd} is input drive control torque, while η_r and η_d are power efficiency coefficients for the drive-carrier, i.e. ring-carrier power flows (see Figure 2).

Substituting the second of equations (6) in the first one, and taking into account that δq_d and δq_r are independent variations yields

$$\begin{bmatrix} \eta_d J_d + Jk^2 & Jk(1-k) \\ Jk(1-k) & \eta_r J_r + J(1-k)^2 \end{bmatrix} \begin{Bmatrix} \ddot{q}_d \\ \ddot{q}_r \end{Bmatrix} + \begin{bmatrix} \eta_d b_d + bk^2 & bk(1-k) \\ bk(1-k) & \eta_r b + b(1-k)^2 \end{bmatrix} \begin{Bmatrix} \dot{q}_d \\ \dot{q}_r \end{Bmatrix} = \begin{Bmatrix} \eta_d \tau_{cd} - k\tau \\ \eta_r \tau_r - (1-k)\tau \end{Bmatrix} \tag{7}$$

Without losing generality, we will neglect the energy losses and rotors dynamic effects, and thus obtain the balance of external torques acting upon a differential gear in the form

$$\tau_{cd} = k\tau; \quad \tau_r = (1-k)\,\tau; \quad \tau_{cd} + \tau_r - \tau = 0 \tag{8}$$

In the parallel structure represented in (Figure 5), the power flow in the second gear, attached to the joint 2, runs from the sun-gear (drive) and the carrier (joint-shaft) towards the ring-gear (common gear shaft).

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The above relations will be utilized for deriving dynamic models of basic IPAD structures. For the sake of simplicity only the basic mechanisms (Figures 3–5) will be considered. The dynamic model of serial two-link manipulator can be presented as

$$\mathbf{H}(q)\ddot{\mathbf{q}} + \mathbf{h}(q,\dot{q}) = \tau + \mathbf{J}^T\mathbf{F} \tag{9}$$

where $\mathbf{H}(q)$ is the robot inertia matrix, $\mathbf{h}(q,\dot{q})$ vector of Coriolis and centrifugal forces, $\mathbf{F}$ is the external force exerted by the human and $\mathbf{J}$ is the manipulator Jacobian matrix. For the considered 2-DOFs manipulators this equation has the form

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{Bmatrix} + \begin{Bmatrix} h_1(\dot{q}_1,\dot{q}_2) \\ h_2(\dot{q}_1,\dot{q}_2) \end{Bmatrix}$$

$$= \begin{Bmatrix} \tau_1 \\ \tau_2 \end{Bmatrix} + \begin{bmatrix} J_{11} & J_{21} \\ J_{12} & J_{22} \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} \tag{10}$$

The explicit expressions for the above model matrices and vectors are relatively simple, and have been therefore omitted (they can be found in several literature, e.g. reference [9]. It should also be noted that joint torque components τ_1, τ_2 do not represent actuator torques (the joint 2 of the mechanism in Figure 3 is not actuated), rather, they represent the equivalent torques reduced at manipulator joint shafts. Based on the above equations and differential gear dynamics (7–8), we can write the following for the serial manipulator sketched in (Figure 3)

$$\begin{aligned} \tau_{r1} &= -\tau_2 = -H_{21}\ddot{q}_1 - H_{22}\ddot{q}_2 - h_2(\ddot{q}_1,\dot{q}_2) + J_{12}F_x \\ &\quad + J_{22}F_y = (1-k)\tau_1 \\ \tau_{cd1} &= k\tau_1 \\ \tau_1 &= H_{11}\ddot{q}_1 + H_{12}\ddot{q}_2 + h_1(\dot{q}_1,\dot{q}_2) - J_{12}F_x - J_{21}F_y \end{aligned} \tag{11}$$

As can be remarked, the propagation of external and inertial forces acting on the second link is twofold: through the internal transmission (differential gear) and via the manipulator links.

The dynamic equations for the parallel IPAD have the form

$$\begin{aligned} \tau_{r2} &= -(1-k_2)\tau_2 = \frac{1-k_2}{k_2}\tau_{cd2} \\ \tau_{r1} &= \tau_{r2} = (1-k_1)\tau_1 = \frac{1-k_1}{k_1}\tau_{cd1} \\ \tau_1 &= H_{11}\ddot{q}_1 + H_{12}\ddot{q}_2 + h_1(\dot{q}_1,\dot{q}_2) - J_{12}F_x - J_{21}F_y \\ \tau_2 &= H_{21}\ddot{q}_1 + H_{22}\ddot{q}_2 + h_2(\dot{q}_1,\dot{q}_2) - J_{12}F_x - J_{22}F_y \end{aligned} \tag{12}$$

The models of a five-bar elemental system (Figure 4) have similar forms. The above approach can be easily generalized and formalized for the modelling of arbitrary IPAD structures with n-links like those presented in Figures 6 and 7. The more detailed models of general mechanism, including efficiency, rotor inertia, payload dynamics and friction effects, are presented in the FhG MaVo Project: "Intelligent Production Systems", (see the report D. Šurdilovic, L. Zhang "Toolbox for modelling and simulation of new intelligent power-assist systems with differential gears", Project report IPK-KOB-0302, available by request from the authors). A toolbox for modelling and simulation has also been developed and implemented in the Simulink.

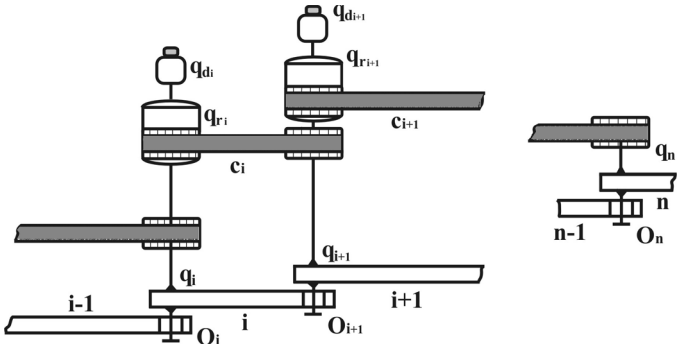


Fig. 6. General serial IPAD structure.

5. CONTROL APPROACHES

As already mentioned, an IPAD control system should meet the following specific goals: path-guidance and power-assist functions. Certainly, the common control goals, such as stability, performance and robustness of manipulator human interaction, have to be ensured too. This section considers the specific goals, in particular, the realization of the path guidance function.

The realization of path guidance is based on the incremental system model defining the position rate of changes in Cartesian and joint spaces related by manipulator Jacobian

$$\Delta\mathbf{x} = \mathbf{J}\Delta\mathbf{q} \tag{13}$$

In IPAD systems the kinematic constraints equation should also be considered; for example, for the 2-DOF system in (Figure 3)

$$\Delta q_1 = k\Delta q_d + (1-k)\Delta q_2 \tag{14}$$

or in a general form for the n-links serial structure (Figure 6)

$$\mathbf{A}\Delta\mathbf{q} = \mathbf{K}\Delta\mathbf{q}_d \tag{15}$$

where $\mathbf{K} = diag(k_1, Kk_{n-1})$ and $\mathbf{A}$ is a band-diagonal $(n-1\times n)$ matrix with elements $A_{ii} = k_i, A_{i,i+1} = 1-k_i$.

The path-guidance control consists of the planning the nominal trajectory within the robot working space as well as

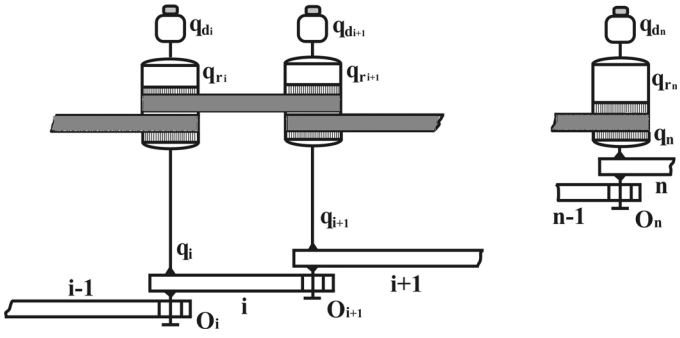


Fig. 7. General parallel structure.

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it's realization. Unlike the conventional robotic systems, and especially for the IPADs, the nominal path defines only geometrical relation but not velocity profiles and timing. This is due to the fact that the path is defined by human movement and cannot generally be predicted. The actual position of the point of interest is determined by using a position sensor in robot's joints. Since the nominal motion is not prescribed, the main problem is the computation of the position error in the considered time instance. In principle, this problem is not unique and various approaches may be applied. The usual strategy is to consider the closest point at the nominal trajectory. Several efficient algorithms, which are suitable for real-time computations of neighbouring points for different 2D and 3D trajectories are also developed in the FhG MaVo Project: "Intelligent Production Systems" (see the above mentioned report).

However, that is not a universal algorithm. For example in five-bar cobots with high gear ratios the actual drive velocity is almost equally split into the main mechanisms link rotation velocities. As sketched in Figure 8, this defines possible motion direction. Therefore, it is convenient to compute the position error along this direction. In this case the choice of the closest point is not compatible with the system manipulability and may cause a worst tracking performance.

Once the position error is computed, we can obtain drive position errors based on (13–14) that can be controlled to zero by using appropriate control, e.g. $\tau_{cd} = PID(\Delta \mathbf{q}_d$. More complex algorithms can also be applied. The inertia managing algorithms are mainly based on the dynamic models (7–12) and feed-forward compensation algorithms. The use of impedance control[10,11] is also possible for reducing effective inertia (by realizing a target system behaviour). In this way the compliant virtual walls can also be realized.

Power-assist control functions require the exertion of active forces, e.g. to compensate for inertial forces (inertia management) and thus to support human efforts. In the IPAD with parallel structures this can be realized by splitting the motion-guidance and power-assist functions among drives. The background for controlling provides the dynamic model (12). Various algorithms, such as feed-forward compensation may be applied. The development of inertia managing algorithms is still in the progress, and due to limited space will not be addressed here.

The stability of interaction between human and IPAD is essential for the system's function. The system passivity or passivation control represents the key paradigm to ensure stable interaction. Robust control design approach, effectually applied in industrial robotic and haptic admittance displays[10–11] can also be applied. These problems also cannot be considered here.

6. EXPERIMENTS WITH A FIRST FUNCTIONAL PROTOTYPE

In order to demonstrate the feasibility of the new IPAD system, a functional prototype (Figure 9) in the form of a simple five-bar mechanism is realized. The control system is implemented in dSPACE and Matlab/Simulink rapid control prototyping environment. Since both base points (Figure 8) coincide, this prototype in the "passive-mode" (with fixed drive) can only realize a circular planar trajectory around $A_0 \equiv B_0$ (located in the origin of the coordinate system in Figure 10). In the "robot-mode", however, an arbitrary

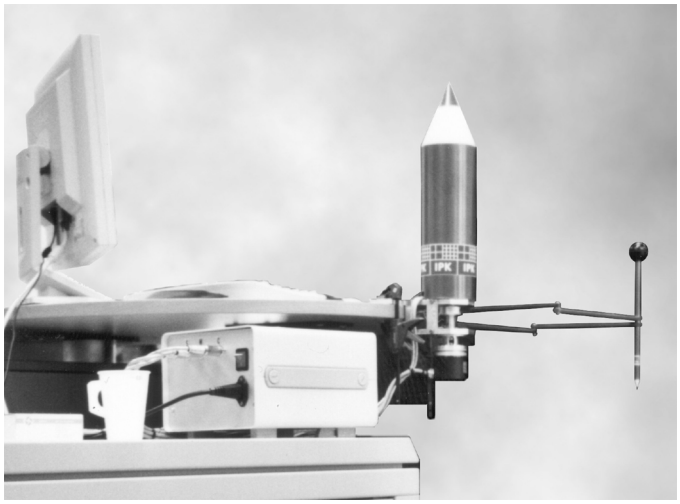


Fig. 9. Functional prototype overview.

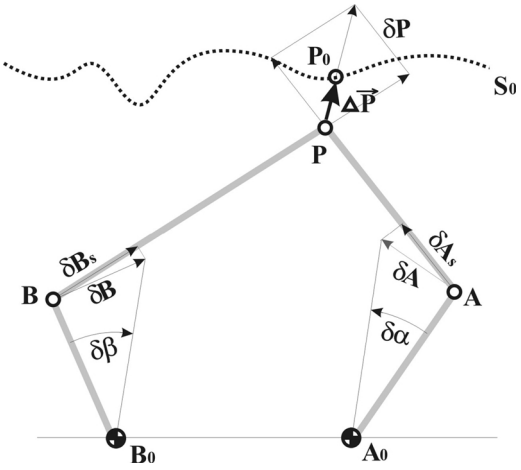


Fig. 8. Position error in five-bar mechanism.

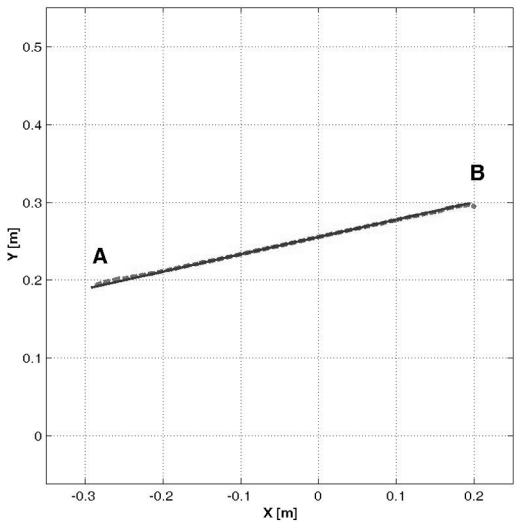


Fig. 10. Linear path tracking experiment.

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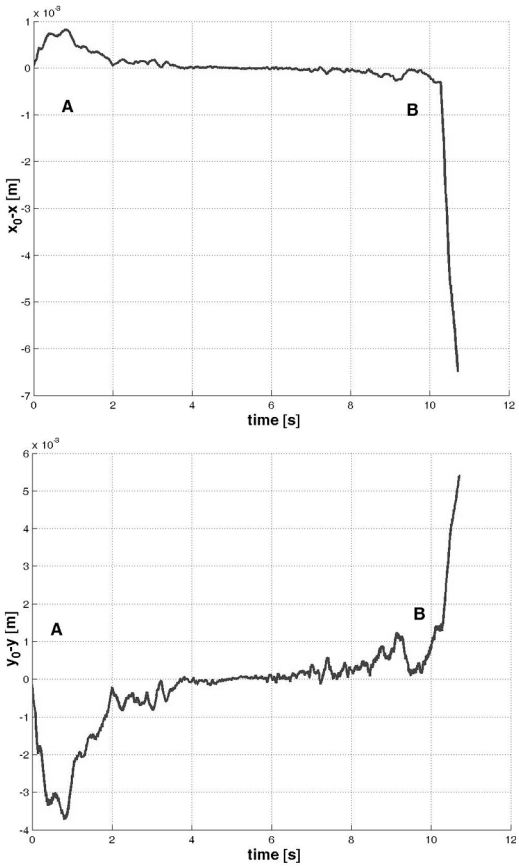


Fig. 11. Position errors in X and Y directions.

virtual trajectory ("virtual wall") can be followed. The example in Figure 10 demonstrates tracking of a linear path between points A and B. Thereby the operator pushes the system in the x-direction (from A to B), while the controller redirects the motion along the virtual path. The positions errors in both directions are shown in (Figure 11). Relatively good tracking accuracy has been achieved with a simple proportional controller. The deviations from the linear path are somewhat higher at the start of the movement. When the end-point has been reached, the control is switched off and the system can move further along the corresponding circle path (in that case it is reasonable to brake the system in practice).

The first experiments have demonstrated that for achieving relatively good performance, a proper selection of drives, sensors, as well as a higher sampling rate is essential.

7. CONCLUSION

This paper presents a novel cobotic system with differential CVT. The new system is significantly cheaper, simpler to control and more efficient than cobots with S-CVTs. Both path-guidance and power-assist functions can be simply realized with the new system. Basic structures, kinematic and dynamic models, as well as control algorithms, which are essential for design, control synthesis and control of the system, are briefly presented in the paper.

The first experiments based on a functional prototype have demonstrated the feasibility and reliability of the new



Fig. 12. First industrial prototype layout.

interactive system concepts. The development of the first industrial prototype (Figure 12) systems actually running at IPK, will contribute to further improving control functions, testing and better understanding of achievable system performance. The specified research goal will be focussed on stable interaction and realization of compliance virtual surfaces based on previous researches,[10,11] as well as on programming (learning) the operator skills. For practical applications, the development of a reliable and functional operator interface is also essential.

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