Robotics and Automation Applications of Drives and Converters

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Invited Paper

The current design limits of power electronics have a significant effect on robotics and automation applications of drives and converters. This paper treats the major design limits that include dynamic range, reliability of power electronics, precision engineering and reliability, productivity and reliability, and drive motion control standards. For each of these limits, the paper identifies and discusses the salient issues and relates them to promising new technologies and, thus, to the future challenges in power electronic systems.

Keywords**—***Contactless power delivery, direct drive motors, dynamic range limits, dynamic stiffness, operation in limits, power electronics reliability, precision motion control, self-sensing methods, sensorless control, thermal control of semiconductors.*

I. INTRODUCTION

The fundamental issues in industrial automation and robotic applications of drives and converters can be related directly to basic limitations of current power electronic designs. The primary limitations are as follows:

- dynamic range of power electronics;
- reliability of power electronic systems;
- precision engineering and reliability;
- productivity and reliability;
- motion control standardization.

The dynamic range of power electronics refers to the limits placed on drives and converters that commonly are imposed to protect the power devices. These limits are not consistent with the needs of most automation and robotics applications.

The reliability of power electronic systems takes the dynamic limits issue a step further and examines how these limits could be altered in order to achieve a more reliable power electronic drive or converter, consistent with automation and robotics application needs.

The precision engineering and reliability discussion presents a set of technology opportunities for automation and robotics applications. Each of these would remove some existing precision limits while also impacting reliability. Each of these is shown to rely on power electronic converters, as well as other technologies to be successful.

The productivity and reliability section presents a network style approach to a classic automation system productivity problem: material transfer. The revolutionary solution presented is seen to depend heavily on drives and power converters, which implies a need for a focus on reliability.

The motion control discussion centers on the stifling effects of standardization of drive controls for motion in automation applications. The section presents a set of well-developed methods which could well form the basis for a changed set of drive control features.

The overall goal of this paper is to address these issues identifying some of the best available technology and the technologies where ongoing research opportunities exist.

The paper is set up to discuss each of these limitations and assess the dominant issues that need further effort. Where possible, the potential approaches for needed improvements in power electronic drives and converters are identified, with a focus on either recent or ongoing published research work.

II. DYNAMIC RANGE OF POWER ELECTRONICS

To identify this issue in automation and robotics applications of drives and converters, it is instructive to examine the classical drive control structure in use today. Fig. 1 shows this in a functional block diagram format.

This model shows how a classical, cascaded loop, control structure is used. The innermost loop is the current loop, which is driven in cascade by the field oriented controller,

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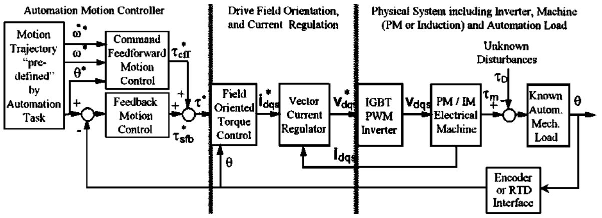

Fig. 1. Block diagram of the *de facto* industry standard, cascaded loop, automation, and robotics controller.

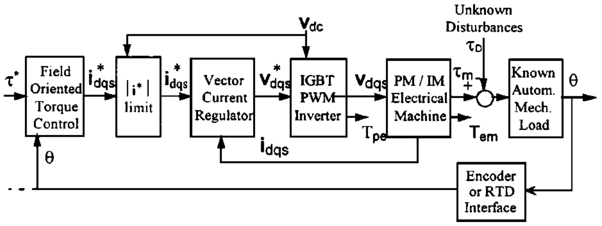

Fig. 2. Block diagram of the drive control functions, especially focussing on the current limit function for the current loop controller.

which in turn is driven by the motion controller. The feedforward controller functions are included to meet the dynamic motion control accuracy requirements for the most demanding automation applications.

Dynamic range requirements for industrial automation are extreme. Actual process intervals are often quite slow because of process limits, e.g., paint cannot be applied with a fire hose. During actual process intervals, the torque demands are often quite low. To minimize the nonproductive time, all nonprocess motion (such as resetting an arm to an initial position) would ideally be accomplished in "nearly zero" time. This implies that an extremely high torque profile should be provided by the controller for a short period to achieve the desired nonprocess motion. An ideally designed feedforward controller would immediately request such torque. A feedback motion controller without feedforward would lag, producing motion errors but converging to values that are also very high.

Within the cascaded drive control, the high peak torque commands would produce extremely high current commands. However the power electronic switches are not ideal and have very real temperature limits that dictate the losses which they can sustain. Thus, the drive's inverter designer generally implements a simple current limit. This is shown schematically in Fig. 2.

The current limit is often a simple saturation (clipping) function. This limit is most commonly designed to be twice the rated, steady-state current of the drive. It is well recognized that this limit cannot always be met, especially at high speeds because of bus voltage limitations, unless dynamic control of field weakening is implemented.

Assuming dynamic control of field weakening is implemented, various methods of control have been suggested to handle the current limit. One method simply modifies the current reference to make it feasible, given the inductance of the motor and the bus voltage. This method is referred to as that of "feasible references" [1]. Another method uses artificial intelligence to select the best possible inverter output voltage, $\mathbf{v}^*_{dqs}$ to minimize either the vector amplitude or vector position error of the resulting current [2].

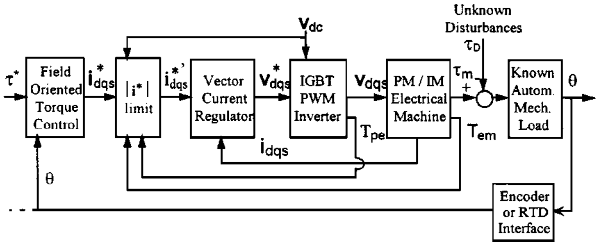

Fig. 3. Block diagram of a more advanced automation and robotics controller which recognizes the power converter thermal limits.

It should be noted that such current limits of the power converter are often a major limitation in the performance of the automation system. Thus, it is instructive to examine what additional opportunities might possibly exist for further improvements. From Fig. 2, it should be noted that two temperatures are included, the device temperature, T_{pe} and the machine temperature, T_{em}. These are the underlying issues in that the temperatures of the device and the machine are the real physical limit, not a fixed value of current. Fig. 3 shows another possibility which focuses on this opportunity of thermal average and peak-to-peak limits as the innermost limit function with current merely serving as the controller intermediate variable that is consistent with maintaining field orientation.

This control methodology is still in its infancy but shows promise as a means of more fully utilizing the thermal limit of the power semiconductor as well as of the machine. In both of these cases, observers and neural networks are the likely candidates for implementation of much of this work, in addition to a few, judiciously placed thermal sensors.

In summary, the dynamic range limitation, as currently implemented in power converters, is not well suited to automation and robotics applications. However, real opportunities exist for improved automation performance if the physical properties of the devices and electrical machine are more fully included in the limiting functions.

The dynamic limitations of power electronics are inherently also related to reliability concerns, which are addressed in the following section.

III. RELIABILITY OF POWER ELECTRONICS

Reliability of automated processes is paramount. A process shutdown due to any reason is economically unacceptable. Sustained operation with limited capability is much more acceptable. The existing controls for power electronic converters are primarily designed for shutdown style protection of the power electronics and not for sustained limited capacity operation of the process. This process shutdown potential makes it difficult for industry to accept higher levels of power electronics dependency.

Multiple causes for failures exist, but in a recent benchmarking study for high-performance drives [4], it was found that two causes were overwhelming: thermal overload

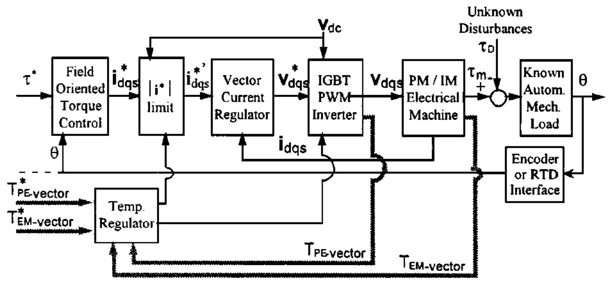

Fig. 4. Block diagram of a more advanced controller which regulates the temperatures for sustained limit operation.

and unexpected application-dependent problems. It seems reasonable that the thermal problems can be addressed by dealing with the root cause mechanisms more directly.

It has been shown that absolute temperature and peak-to-peak temperature cycles of devices, interconnections, interfaces, and components dominate the thermal–mechanical failure mechanisms of power electronics [3]. This suggests an opportunity to actively control the temperature and temperature cycles of devices, interconnects, interfaces, modules, and components as the innermost loop on the power converter. From a purely materials science perspective, a nearly infinite life could be obtained via such active control.

To achieve this methodology, the limit-varying control methodology of Fig. 3 above can be extended to address sustained operation under multiple thermal and thermal–mechanical constraints. These would be imposed by actively controlling temperatures and temperature cycles of devices, interconnections, interfaces, and components. Such control would become the innermost loops and power conversion and motion control would be subordinate to these capacity-reducing constraints. One such structure is shown in Fig. 4 where the thermal–mechatronics of both the power electronics converter and the machine are regulated, and actively limit the power conversion of the drive including both conduction losses and switching losses.

The thermal control loops actively limit the power conversion of the drive including both conduction losses and switching losses and maintain “tripless” drive operation in limits that are sustainable on a continuous basis.

This type of sustained, “tripless” control could substantially broaden the automation acceptance of power electronic solutions. To maintain proper process control, it would also have to be integrated with the automation motion controller so that process parameters were maintained if motion were slowed down to accommodate drive internal thermal limitations.

In summary, reliability of power electronics could strongly benefit from a control-oriented solution whereby failure causes are actively regulated and power conversion subordinated. This solution methodology is indeed a major focus of ongoing research addressing reliability of power electronic systems [5].

The reliability of power electronic systems in automation and robotics applications has a number of dimensions which are unique to special problems in automation. The following sections deal with these automation-specific reliability issues.

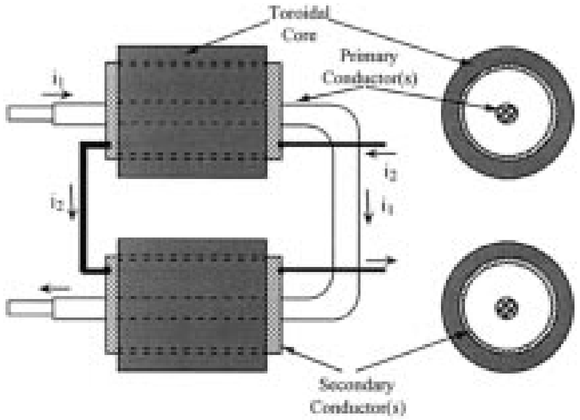

Fig. 5. Coaxial winding transformer suitable for high-frequency, contactless, power transfer.

IV. RELIABILITY AND PRECISION ISSUES

Precision of automation systems translates directly to quality and uniformity of products. This is basic to modern quality-oriented, manufacturing. Thus, to the extent that power electronics can affect the precision, opportunities exist for power electronics to expand its acceptance. The following subsection present opportunities that address both reliability and precision issues in automation and robotics.

A. Contactless Power Transfer in Automation and Robotics

One general problem in automation systems, but especially in robotics, is the need to transfer power and signals between moving axes where relative motion occurs. In automation and robotics with primarily orthogonal, translational motion such as on CNC machines and gantry robots, wire-supporting mechanisms are used to protect and guide the power and signal wires. They add extra load to the axis drives, affect the dynamic performance which can be achieved, and affect precision unless this load is adequately compensated. In general-purpose robots where rotational joints are common, the connections from link-to-link are often made with cables routed internal to the joints and links. The limited flexure of the fixed cables generally limits the motion range of the joints in addition to producing additional forces degrading precision of the robotic arm.

In both automation cases, it would be desirable to eliminate the hard cable connections, both from a reliability perspective and from a precision engineering perspective.

Power electronics can be used to provide contactless power and signal transfer with none of the cable connection dynamic or accuracy compromises. Several such solutions have already been developed. For translational motion, the use of coaxial winding transformers (CWTs), as shown in Fig. 5, have been used to provide a viable, and compact solution with almost no air gap tolerance problems [6], [7].

Fig. 6 shows a typical CWT translational, contactless power conversion setup, including high-frequency power electronic converters needed to make the system compact.

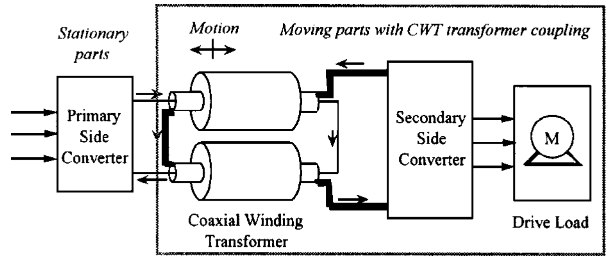

Fig. 6. Block diagram of a high-frequency, contactless, power transfer system for translational motion.

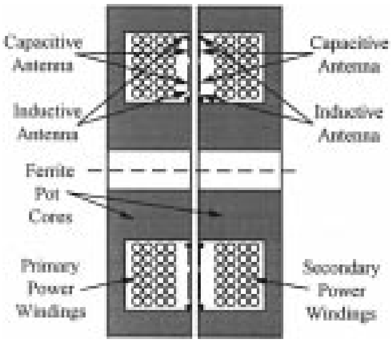

Fig. 7. Cross section of pot core transformer suitable for high-frequency, contactless, power and signal transfer in rotational joints.

For rotational joints, a high-frequency pot core transformer of more traditional design can also be used [8]. However, the air gap tolerance becomes more significant. Fig. 7 shows the cross section of such a transformer with additional inductive and capacitive antennae suitable for control signal as well as power transfer in robot arm rotational joints.

In both cases, power electronics allows the transformers to be very compact by using high frequencies, in the 1–10-kHz range for the power transfer with conventional carrier signal frequencies of 25 MHz used for the signal transmission system with its associated, conventional, signal modulation, and demodulation technologies.

The tradeoffs between such power electronic, contactless power transfer systems and power and signal cabling can be viewed from cost perspective as well as precision and reliability. This technology has great promise to improve system performance and reliability and perhaps to lower cost.

B. Self-Sensing Motor Drives in High-Performance Automation

Another reliability and precision issue is the use of sensors in high-performance automation that is subjected to substantial vibration and dynamic disturbance inputs. In general, sensor leads are fine gauge wire and thus are inherently fragile, especially at stress points where connectors are fastened. In current automation systems, they are well protected but at some cost. A considerable opportunity exists if the sensors can be integrated into the power electronics, without requiring the traditional sensor leads.

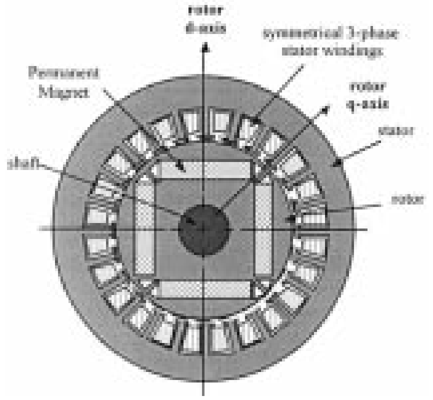

Fig. 8. Cross section of a commercial buried magnet PM synchronous servomotor rotor with inherent saliency.

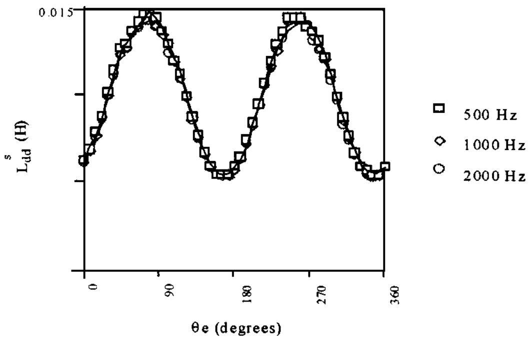

Fig. 9. Self-inductance of unmodified buried magnet PMS motor with inherent saliency sufficient for self-sensing.

In most high-performance automation and robotics applications where high-precision position control is needed, low-power (1–10 kW), ac permanent magnet (PM) servo motors are the norm. Two types of PM motors are commonly used, based on the magnet mounting; either on the rotor surface (SPM) or interior to the rotor (IPM). Fig. 8 shows the cross section of a commercial IPM AC servo.

For IPM AC motors, there is inherently a large amount of magnetic saliency. This inherent rotor saliency can be used as the sensor using so-called "self-sensing" techniques [9]–[18]. Fig. 9 shows the magnitude of this saliency for a typical IPM servo.

These methods use the saliency as if it were a magnetic resolver (the most commonly used feedback sensor for PM drives). The self-sensing methods use only the power leads for sensing information. The self-sensing method (as well as other similar techniques [19]–[25], also summarized in [48], [49]) uses the power converter to superimpose a carrier frequency voltage (or current) signal on the fundamental component, as shown in Fig. 10.

The carrier frequency current signal is separated from the power conversion's fundamental component in the motor controller by synchronous frame filters and fed to the equivalent to an improved, zero-lag, resolver-to-digital converter, usually implemented in the drive software [15], [16].

Fig. 11 shows the image tracking observer, i.e., an improved resolver-to-digital converter, which actually tracks

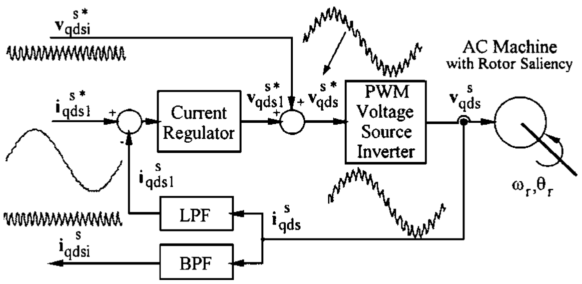

Fig. 10. Self-sensing, carrier frequency, excitation voltage superimposed on the fundamental.

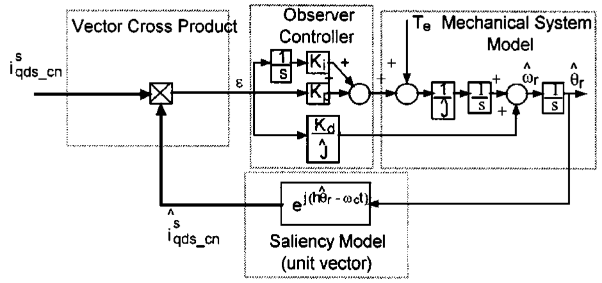

Fig. 11. Tracking observer for the estimation of rotor position in a machine with a single harmonic saliency image.

the electromagnetic image of the rotor, thus, it can easily handle harmonic distortion in the form of the saliency.

This methodology has shown excellent experimental and field results. Fig. 12 shows a comparison of the standard resolver and the "self-sensing" resolver for a typical IPM servo [18].

One key issue to the use of this technique is the difficulty in assimilating a solution combining three distinct fields, power electronics, electric machine design, and image tracking. The perceived combined risk makes the reliability of this solution technology more difficult to assess.

Since the sensor, connectors, and cable become reliability issues in only those cases of extreme vibration or temperature variations, not all automation equipment will benefit from this self-sensing technology. Furthermore, the precision limits of self-sensing are still a research topic. Thus, the methodology is not yet mature enough to have a full complement of advantages (i.e., precision) to offer in addition to reliability and cost which it has demonstrated.

For completeness, it should be noted that fundamental component sensorless methods, including standard direct torque control (summarized in [48] and [49]) are regularly used for average speed control in applications where high-precision motion control is not needed, such as spindle motor applications within an automated system such as a machine tool.

C. Direct Drive Motors and Electromagnetic Bearings

Another promising technology which has long term precision and reliability advantages for automation and robotic applications of drives and power converters is the use of direct drive motors which are integrated into the design of the automation equipment. Such drives could theoretically remove the problems associated with ball screw maximum speed limits or harmonic gear drive torque limits. Historically, this type of equipment has evolved in custom, precision engineering applications, such as in direct drive robot grippers [26], or in direct drive stages for semiconductor mask lithography [27], [28].

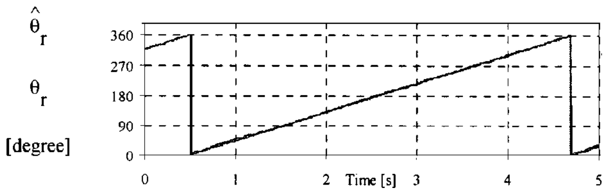

Fig. 12. Conventional resolver and self-sensing resolver position signals for IPM rotor position at 14.4 rpm.

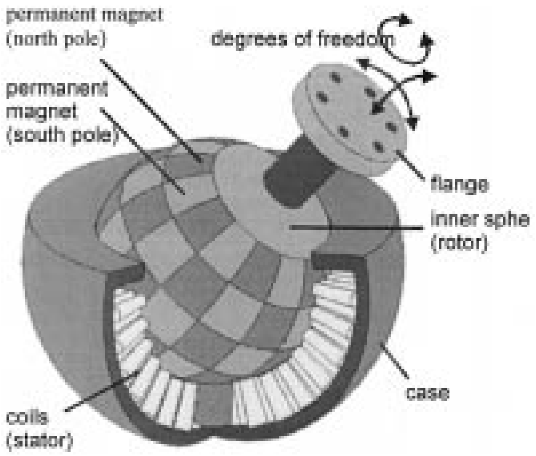

Fig. 13. Direct drive, spherical motor intended for the final three angular degrees-of-freedom on general purpose robots.

More recently, this has evolved into multi-axes direct drive spherical motors for robotic applications where the three degrees of angular freedom (classical yaw, pitch, and roll) are incorporated into one special machine. Fig. 13 shows this 3 DOF, direct drive, spherical motor [29].

For this spherical machine a 96-phase power electronic converter is used to simultaneously control all of the 96 poles so that the space varying flux linkages can be precisely controlled. This machine has limited angular range in the pitch and roll axes, but infinite rotational capability in the yaw axis. It is intended to replace the final joint in robots used for precision automation tasks in manufacturing, such as grinding and polishing. The spherical motor uses hystrostatic bearings and routes the oil used in the bearing pads such that it also cools the 96 coils.

This technology can also be extended, as it has in other cases [30] to include electromagnetic bearings to replace the hydrostatic bearings or even more conventional rolling element bearings. This dimension provides a further opportunity for power electronics but also another significant set of challenges.

It is well understood that rolling element, antifriction bearings used in most forms of automation must be preloaded to obtain adequate kinematic accuracy and adequate joint stiffness. The joint stiffness is preload dependent and must be high enough such that load-dependent deformation is negligible. The equivalent stiffness of preloaded antifriction bearings or of hydrostatic bearings is not generally achievable by actively controlled, electromagnetic bearings. Thus, the application must significantly benefit from the secondary properties which electromagnetic bearings offer. One secondary benefit of great precision engineering value is that coulomb friction and hysteresis forces are practically zero on well-designed electromagnetic bearings. Since the friction coulomb forces and hysteresis in preloaded, antifriction bearings are considerable, this benefit can help to justify electromagnetic bearings. This secondary benefit is of critical importance when either very high speed operation (such as very high speed grinding spindles) or varying temperature operation is needed for the application. Temperature variations and speed are critical for conventional preloaded, rolling element bearings but are insignificant for electromagnetic bearings since except for secondary effects, none of the electromagnetic bearing properties change with temperature.

The challenge for power electronic converters used in electromagnetic bearings as well as in direct drive motors, is the location of thermal losses and their impact on precision. In general, the location of thermal losses is quite significant in determining the desired symmetry of thermal growth. Thus, one can imagine that in the case of the hydraulically cooled spherical motor used at the end of a gantry robot arm that the location of the 96-leg power electronic converter would be a significant issue. If this were integrated with contactless power and signal couplings in the gantry axes, a significant power distribution challenge and potential opportunity arises. The ability to locate the heat sources (losses) at strategic positions, should be used to advantage in developing the next generation of such power electronic systems. Thus, it becomes imperative to maintain flexibility in packaging of the power electronics. Even more important, it becomes imperative to develop good thermal-mechanical models of power electronic systems and to use these models in developing product designs with integrated, direct drive motors, contactless power transfer couplings, and electromagnetic bearings.

In summary, the power converters and controls needed for precision engineered automation should be expected to increase substantially and the inherent packaging and thermal-mechatronic issues in power electronic systems should come even stronger to the forefront of the technical challenges.

V. RELIABILITY AND PRODUCTIVITY ISSUES

Some technological advances in the automation and robotics application of power electronics most directly affect productivity of automation systems. The following subsection identifies a major opportunity of this type.

A. Linear Motor Drives for Material Transfer in Automation

Material flow in manufacturing has yet to benefit from the "interconnected network" methodology now widely accepted for data. One major reason has been a very limited perspective on how such "networks" could be constructed to handle real materials, and not just packets of data. One such methodology has been investigated both theoretically and experimentally and is shown conceptually in Fig. 14 [31], [32].

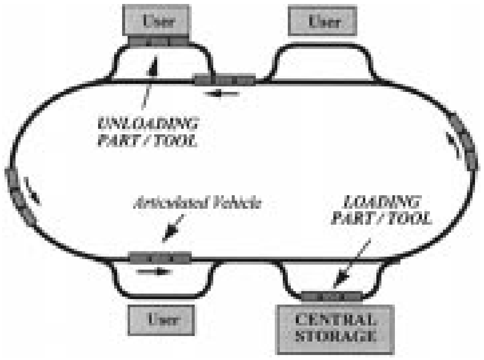

Fig. 14. Material transport network system based on magnetical propelled, magnetically steered, transverse flux, linear induction motors.

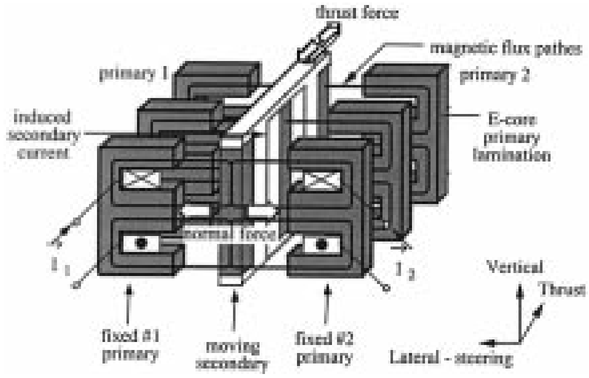

Fig. 15. Linear, transverse flux, induction motors of the moving secondary, fixed primary configuration.

From a high level perspective, the system consists of a grid of high-performance (3 g acceleration, 100 km/hr velocity) linear induction motors (LIMs) which act as the material transfer agents.

In a classical sense, the system has properties similar to the grid of train trunks and locomotives as in a dense European transportation network. Power electronics also has a major role in this system since the power conversion in each section of the grid is actively controlled by individual section, power electronic converters.

The network analogy is also very strong. The system treats the central storage as a "network server" which has the materials (resources) needed for various users and at various times in the network.

The network transfers material (packets) in an autonomous fashion. If a material (part) is requested, the nearest LIM responds by stopping to pick up the part from the central storage (server) and deliver it to the user (interface).

A heterogeneous control architecture allows each LIM material transfer agent to act in an autonomous fashion with knowledge of only limits imposed by its adjacent neighboring agents. This topology has been shown to be very robust [33].

The power conversion technology is quite novel. The individual LIMs are linear, transverse flux, induction motors of the moving secondary, fixed primary configuration, as shown in Fig. 15 [34].

This type of machine is well suited to short lengths and, thus, is also a good fit with short turning radii needed in normal manufacturing facilities.

Each machine is effectively an individual material transporter. The machine is magnetically propelled, and magnetically steered. The two fixed primary windings are thus controlled simultaneously to achieve "field oriented" thrust force control and active bearing control of the normal force. This control of the normal force is used to electromagnetically steer as needed for network entrance and exit ramps, as shown in Fig. 16.

A photo of a functional lab prototype section is shown in Fig. 17 whereby one side of the fixed primary has been removed to show the physical arrangement of the fixed primary core and moving secondary more clearly [31].

This material transport system also utilizes the previously described "self-sensing" methods such that no sensor is needed on the moving secondary. This system relies on a large distributed base of power converters which control any machine in its respective segment. Thus, power conversion, and integration play major roles in this technology.

The cost effectiveness of this network style of material transports system has been carefully investigated [32]. It was shown that such systems would radically reduce the need for highly distributed materials in manufacturing. This is akin to the current standard practice of users accessing server resources rather than having all resources loaded on each user's hard disk. The potential secondary benefits of this technology also include a reduced time to change over technologies since the questions of multiple distributed resources would become mute. The overall potential for this technology for manufacturing is extremely high and as such, this could prove to become a major driver for power converters and drives in automation, much as data networks have become major drivers for reorganization of business operations.

The last issues to address in this paper focus on the role of motion control in automation, and how it currently limits the overall progress of power electronic systems in automation and robotics.

VI. MOTION CONTROL ISSUES

The final issue of concern in industrial automation and robotic applications of power electronics is the relatively low performance of industry standard motion controllers. A historical focus on standardization in the industrial motion control architecture has led to the result that the dynamic capability of modern power electronics has not been well utilized.

This standardization may reduce product development costs but it has led to prolonged use of inferior control algorithms in many automation applications and to a lack of appreciation of the dynamic capabilities of modern power electronics. This issue represents an interesting opportunity to both advance the productivity of automation and to economically justify the use of advanced power electronic devices and systems.

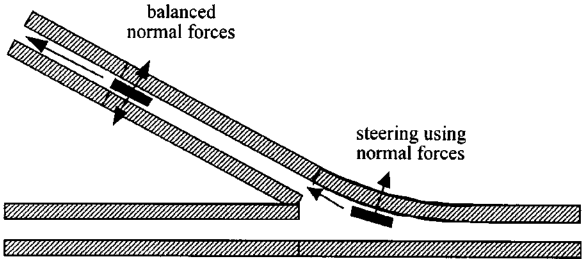

Fig. 16. Top view of network entrance and exit ramps for the LIM-based, high-speed, material transport network system.

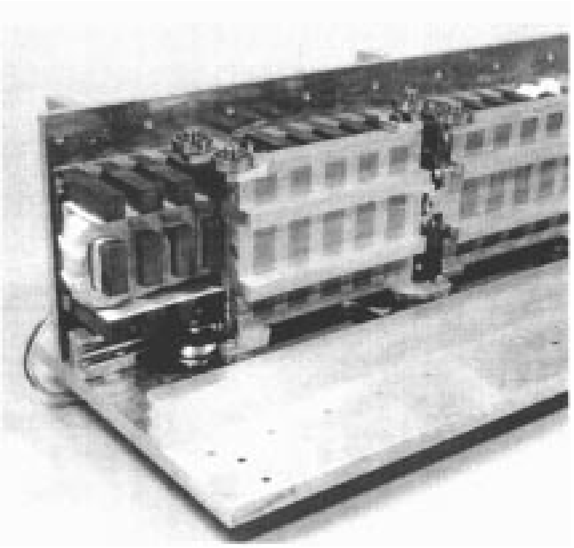

Fig. 17. Laboratory prototype of the transverse flux, LIM material transfer system showing one fixed primary side and the moving secondary.

Some very appropriate modern drive control developments have occurred in state variable control design methodology, state and disturbance observer design, and disturbance input decoupling control.

The evaluation here will focus principally on motion control using ac servo drives. The current, de facto industry standard, cascaded loop motion control structure is shown in Fig. 18.

To explore advanced drive controls, this section will evaluate each of the main themes cited above and present each approach relative to this classical standard digital motion controller.

A. State Variable Control Design Based on Physical Properties

The *de facto* industry standard controller can easily be redrawn in a state variable format, as shown in Fig. 19 [35]–[39]. Note that the so-called "Velocity Feed Forward," $\overline{\omega}^*_{\mathrm{cff}}$, is actually just the desired reference command, $\overline{\omega}^*$, for the velocity loop. Furthermore, this loop is closed on the average velocity (which is $\overline{\omega} = \Delta\theta/T$ where T is the real

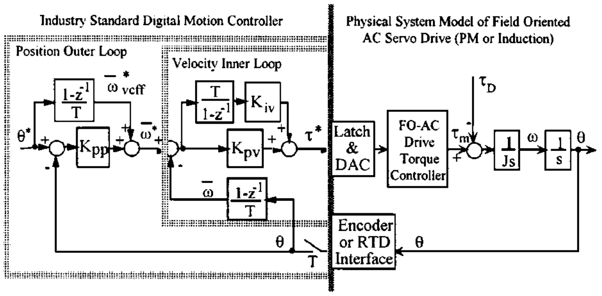

Fig. 18. The *de facto* industry standard, cascaded loop, digital motion controller.

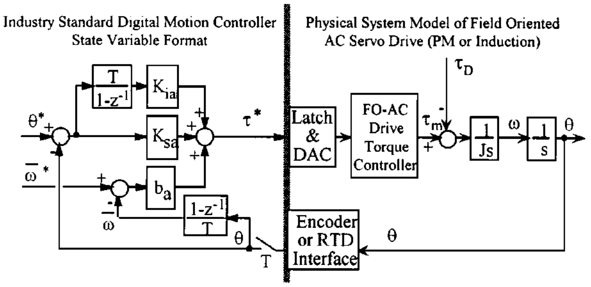

Fig. 19. The industry standard digital motion controller in state variable format.

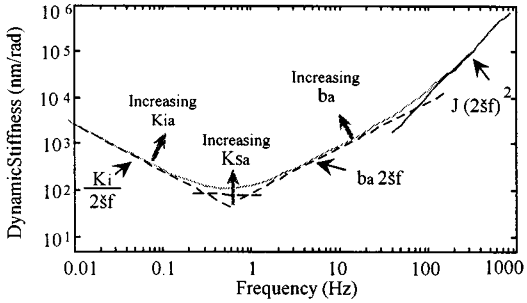

Fig. 20. Dynamic stiffness of the state variable motion controller.

time sample period), not on instantaneous velocity, ω. This state format is equivalent to Fig. 18, where

$$\begin{aligned} b_a(\text{nm/rad/sec}) &= K_{pv} \\ K_{sa}(\text{nm/rad}) &= K_{pp}K_{pv} + K_{iv} \\ K_{ia}(\text{nm/rad}\cdot\text{sec}) &= K_{pp}K_{iv}. \end{aligned}$$

One of the primary benefits to the state variable format is that the state feedback gains all have physical meaning and physical units. Thus, for example, K_{sa} has units of static stiffness (Nm/rad). This means that this controller tuning gain can be checked *in situ* by purely mechanical means.

This insightful feature has proven to make debugging controllers easier and faster. In addition, the disturbance rejection (dynamic stiffness) capability of the drive is now very explicit, as shown in Fig. 20.

While the state variable format helps considerably in tuning the drive and in knowing precisely what disturbance rejection properties it will achieve, the motion command tracking is still error-driven (motion errors must exist for at least some transient time for a steady-state torque to be achieved by the controller). Fig. 21 shows how this error-driven command tracking property can be virtually removed by addition of torque command feedforward.

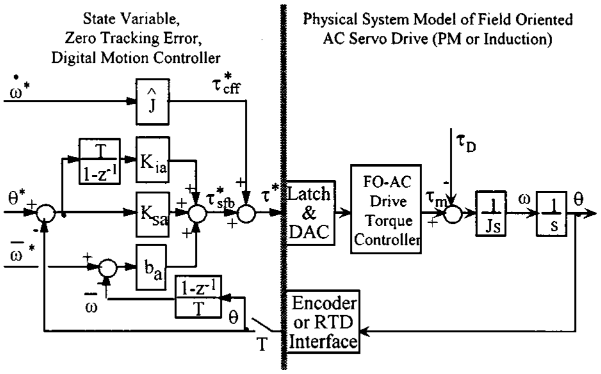

Fig. 21. Torque command feedforward added to the state variable motion controller.

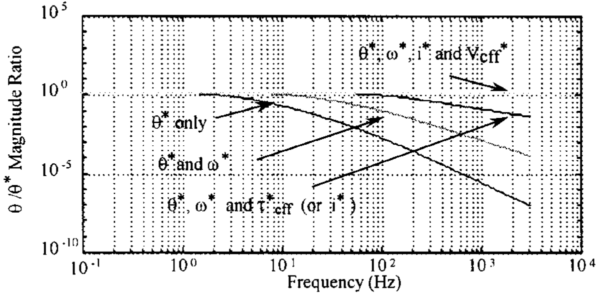

Fig. 22. Command tracking frequency response with torque command feedforward added to the state variable motion controller (assuming feasible command trajectories).

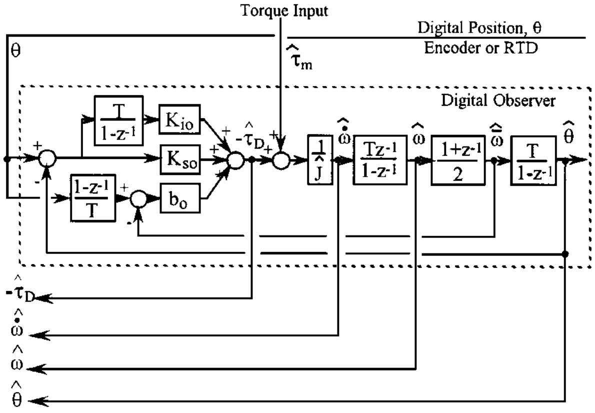

Fig. 23. Digital velocity, position, and disturbance torque observer based on measured digital position (from encoder or resolver) [9], [35], [36], [40].

For this example, the command feedforward torque, τ^*_{cff}, is a linear function, but virtually any nonlinear function can be included. In addition, for a known, feasible trajectory, the command feedforward can be precomputed and placed in a look-up table. This can dramatically lower the implementation expense for automation applications where the trajectory is most often known in advance.

The command tracking frequency response is shown in Fig. 22 for the four commonly used command variants (all assuming feasible trajectories and constant feedback gain tuning). In essence, command feedforward makes command

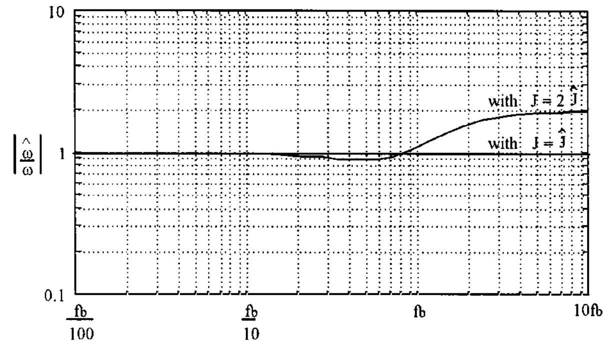

Fig. 24. Estimation accuracy frequency response for velocity observer viewed as a sensor replacement.

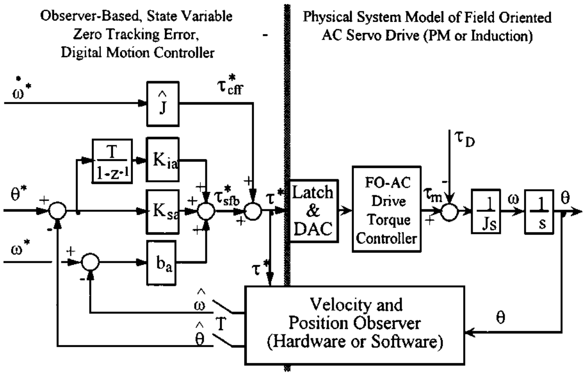

Fig. 25. Digital velocity observer integrated into the state variable motion controller with instantaneous velocity control.

tracking virtually independent of disturbance rejection tuning.

From Fig. 22, it is apparent that each additional term added to the reference command vector improves the command tracking response up to the current regulator bandwidth without affecting noise filtering desired due to sensor and sensor interface limitations. In fact, the torque command feedforward is actually the state reference for the torque producing drive current [36].

As shown in this frequency response plot, the response beyond the current regulator bandwidth could be improved up to the switching frequency limit if voltage command feedforward were also included. Since it is in the feedforward path, feedback noise filtering is unchanged.

B. Velocity and Acceleration Observers

While command feedforward provides command tracking response, the controller state feedback gains determine dynamic stiffness. These gains are limited by feedback quantization and by the inherent lag from average velocity. The lag can be eliminated and the quantization minimized by constructing an observer, as shown in Fig. 23.

Such observers are merely real time models which receive the same inputs as the physical system and are controlled to track the measured states [35], [40]–[42]. They can be viewed as sensor replacements.

For any sensor (replacement) its frequency response is a primary measure of its usefulness. The observer's "estimation accuracy frequency response" is shown in Fig. 24 [40].

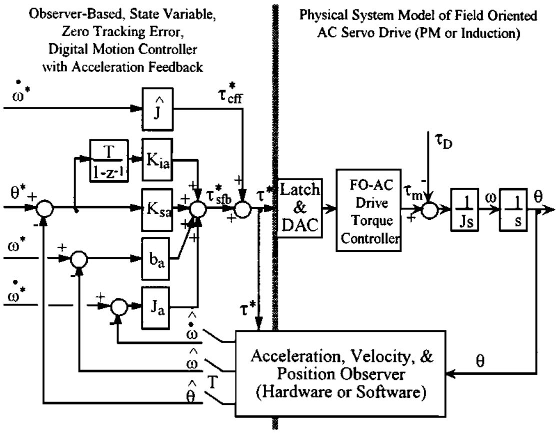

Fig. 26. Digital acceleration observer and active inertia state feedback integrated into a state variable motion controller.

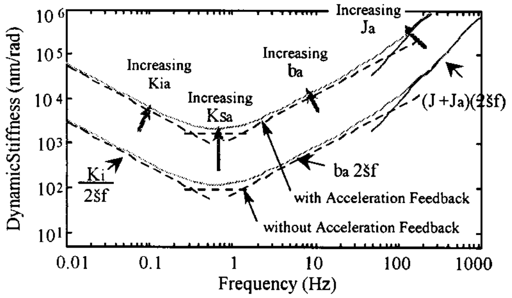

Fig. 27. Dynamic stiffness when acceleration feedback is integrated into the state variable motion controller but bandwidths are held constant.

Within its bandwidth $(f < f_b)$, the estimation accuracy of this observer topology is insensitive to the estimated inertia, $\hat{J}$, and only has a linear error characteristic beyond its bandwidth. Its resolution is dependent on the numerical precision in the observer calculations. Fig. 25 shows this observer integrated into the state variable motion controller whereby instantaneous velocity is now the controlled variable (rather than average velocity).

The observer of Fig. 23 also includes estimation of acceleration [35], [43], [44]. It should be noted that for constant flux, acceleration is the same state variable as the torque-producing current except that it contains disturbance information.

This output of the observer is particularly important since angular acceleration is not readily measured with inexpensive commercial sensors, although sensing methods have been developed [45]. When integrated with the state variable motion controller, as shown in Fig. 26, it is apparent that the feedback gain on acceleration has units of inertia. Thus, it can be viewed as active inertia (or an electronic flywheel).

Fig. 27 shows how the entire dynamic stiffness plot is raised in direct proportion to the added "active inertia, J_a." It indeed acts like a flywheel to disturbance loads.

Another desirable attribute of acceleration feedback is decreased sensitivity to load inertia, which is especially problematic for the newer, low inertia PM ac servos [46]. It has also been shown to be of substantial value in reducing the effect of torsional load resonances [47].

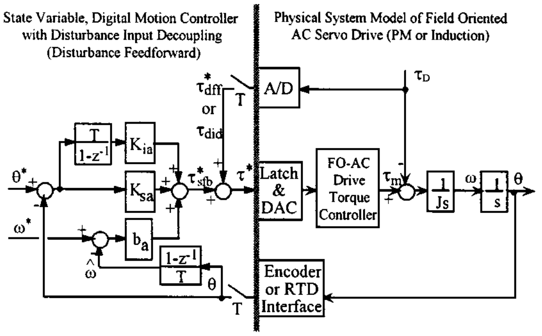

Fig. 28. Disturbance input decoupling integrated into the state variable motion controller via measured disturbance torque.

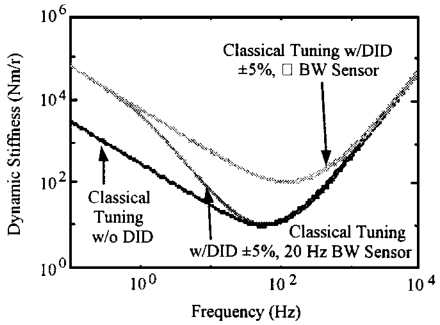

Fig. 29. Dynamic stiffness with disturbance input decoupling via measured disturbance torque of finite accuracy and bandwidth.

C. Torque Disturbance Observers and Disturbance Input Decoupling

In many types of state control applications, it is inexpensive to measure the disturbances and decouple them directly (e.g., decoupling outside temperature from room temperature control, decoupling bus voltage from inverter output voltage, etc.). This technique is often referred to as "disturbance input decoupling" [9]. Fig. 28 shows how this would ideally be done for drives if disturbance torque were measured.

The resulting dynamic stiffness improvement is limited by the accuracy and bandwidth of the disturbance torque measurement, as shown in Fig. 29. The finite accuracy and bandwidth of the measurements limit the amount and frequency range, respectively, of the improvement.

Direct measurement of torque is not an accepted practice since the torque sensor is compliant and thus generally degrades the stiffness of the system (as well as incurring substantial acquisition, installation, and maintenance costs). Thus, an alternative approach uses a "disturbance torque observer" to estimate the disturbance torque which is then used for disturbance input decoupling. The digital position measurement-based observer of Fig. 23 [9] can be seen to also achieve this $\hat{\tau}_D$ estimation.

The observer of Fig. 23 yields steady-state and dynamic estimates of disturbance torque. However, from its topology its $\hat{\tau}_D$ estimate will lag behind the actual. This is in direct contrast to the $\hat{\dot{\omega}}$, $\hat{\omega}$, and $\hat{\theta}$ estimates which will track with zero lag (refer to Fig. 24). This is a direct result of the fact that the $\hat{\tau}_m$ acts as the correct feedforward input to the observer for estimating states but it contains no disturbance information. Disturbance information is conveyed strictly by the measured θ (and ω) state.

In summary, observers of sufficient bandwidth can be used to estimate motion states and disturbance inputs with very beneficial impact on the disturbance rejection of the drive. The required bandwidth is generally equivalent to the motion control bandwidth.

VII. CONCLUSION

This paper has presented a multifaceted perspective on automation and robotic applications of drives and converters. The key issues and opportunities were related to the primary limitations. The following conclusions were reached.

Problems with the limited dynamic range of power converters can be somewhat mitigated in automation applications by modifying the active limits placed on the converter to more accurately reflect the physical limits.

The reliability of power electronic converters and drives in automation could be enhanced by altering the converter control to actively control the thermal status of the power devices, interfaces, components, and the electrical machines.

Contactless, high-frequency power and signal transfer could substantially impact the use of power converters in automation and robotic systems. Reliability and precision improvements could be realized.

Self-sensing motor drives could improve the reliability and reduce costs in automation and robotics applications subjected to substantial vibration and dynamic loads. This methodology relies strongly on good integration of power converters, machines, and image tracking technologies.

Direct drive motors and electromagnetic bearings can offer substantial precision advantages over their classical counterparts. Thermal–mechatronic integration of such systems needs to evolve to support this opportunity.

Network-style material transport systems based on linear motors have been proposed and evolved to show substantial productivity advantages, analogous to their digital counterparts. This technology could well drive power converter needs in future automation systems.

Motion control methodologies have advanced significantly at least within a research laboratory context. These methods need to find their way into drive controls so that improved accuracy and disturbance rejection are intrinsic in all modern automation and control systems.

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