2005 American Control Conference
June 8-10, 2005. Portland, OR, USA



# Control Systems Challenges in the HP Personal Ink Jet Printing Application

Doug Harriman (doug.harriman@hp.com)
Hewlett-Packard Company

*Abstract*— **This paper presents several of the major control systems challenges faced by the Hewlett-Packard Company in designing competitive ink jet mechanisms for today's desktop printer and multifunction device market. A discussion of the physical plants under control, as well as the performance goals and the constraints on the control system is provided. It is hoped that this paper will afford the control systems community a deeper understanding of the problems faced in the ink jet printer industry, and generate interest in solving these problems.**

## I. Introduction

The personal printing market is a multi-billion dollar market worldwide. Within the realm of personal color ink jet printers, the Hewlett-Packard (HP) Company holds a dominant market share. Part of HP's market strength is due to the multiple high quality, high speed print engines which form the basis of a diverse range of products. In order in provide higher print quality (PQ) at faster print speeds, many engineering design challenges must be overcome. Several of these challenges fall within the realm of control systems.

The most interesting challenges revolve around the two axes of motion related to accurately placing ink drops on the print media. These axes are the focus of this paper. The next section of this paper provides a brief overview of the mechanical architectures used in paper and print cartridge drive mechanisms. Following that, a discussion of the control system performance goals is provided, as is a discussion of the constraints placed on the designs. The final section details several classes of problems that are addressable with control systems, the approach of the current designs, and attributes of an improved solution.

## II. Mechanical Drive Architecture Overview

The overwhelming majority of personal ink jet print mechanisms shipped by HP over the last ten years have had similar mechanical drive architectures. This holds for both the paper and print cartridge axes. These systems rely on a permanent magnet, brushed DC motor for torque generation. This motor is driven by a pulse width modulated voltage. Feedback is provided by a quadrature output optical encoder. Specific details unique to each axis are presented below.

### A. Print Media Drive

The print media drive system, Fig. 1, attaches to the motor via a tensioned belt which drives a cluster gear. This gear then drives a second gear attached to the print media feed shaft. The speed reduction from motor to feed shaft is typically about 15:1. The feed shaft has elastomeric rollers which are used to drive the print media. These rollers typically have a circumference of 3 inches. Attached to the feed shaft is an encoder disk. Linear position of the print media is inferred from rotary position of the feed shaft, with a quadrature resolution of 2400 counts per linear inch (CPI).

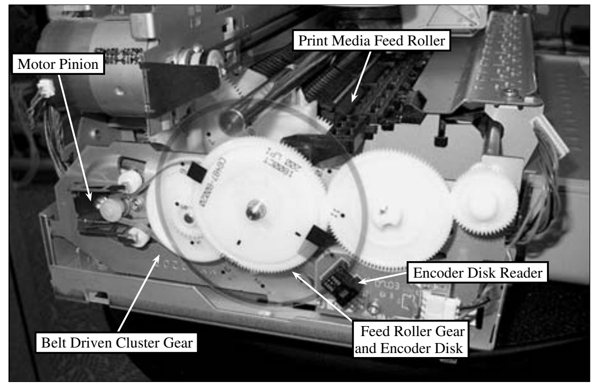


Fig. 1. Print Media Drive on the HP DeskJet 5150

### B. Print Cartridge Drive

The print cartridge carriage, known simply as the carriage, is driven in a reciprocating fashion via a belt attached at one end to the DC motor, and at the other end to a spring tensioned idler pulley, Fig. 2. The carriage guide system consists of two V-bearings riding on a cylindrical rod. These bearings provide very tight control of the carriage rotational orientation with respect to the print media, as no running clearance is required. Finally, an anti-rotation sliding surface is provided either in front of, or behind the rod. A linear encoder strip provides position feedback at a quadrature resolution of 600 CPI.

## III. Control Related Printer Performance Goals

Motion control systems directly affect the overall performance of the printer in a variety of ways. The two most important effects for the consumer are print quality and print speed.

The effects of the print media servo on PQ are readily apparent, as stopping accuracy directly affects the position of ink drops on the media. For high quality printing, this

0-7803-9098-9/05/$25.00 ©2005 AACC 

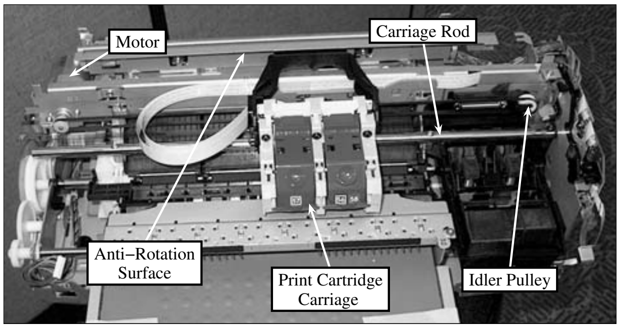


Fig. 2. Pen Carriage Drive on the HP DeskJet 5150

typically means the stopping error should be zero encoder counts.

The print carriage effects on print quality are more subtle. Ink drops are fired while the carriage is in motion. It is very important for the carriage to provide a stable platform from which to fire the drops. This requires carriage motion to be completely in the direction of travel, without any motion in the other two directions or any rotations. More detail about carriage motion trajectory effects on print quality are provided in the next section.

The effects of the control system on print speed are very simple. Obviously, the faster the carriage and print media can be moved, the faster the print job can be completed. High print throughput is a very important competitive specification in the market. HP's current generation of high end ink jet print mechanisms have throughputs of 30 pages per minute (PPM). At such throughput levels, reduction of move times on the order of 10 milliseconds per move will have a significant impact on the rated printer throughput.

## IV. Control Systems Constraints

A diverse set of constraints act on the carriage and print media servo designs. These include physical constraints imparted from the designs of other subsystems, economic constraints due to competitive market pressures, computational constraints set by processor selection and the computation required by the printing process, and plant variation from a variety of sources. All of these constraints must be addressed in order to produce a successful product.

### A. Physical Constraints

Ideally, both axes would have a velocity trajectory providing the minimum time for each move, and would stop with zero position error. Unfortunately, hardware constraints limit performance. The drive electronics restrict the input power, current and voltage to the motor. Fortunately, for the print media axis, there are no other major constraints on system performance.

For the carriage axis, there are two other important constraints which provide a lower bound on the time required to complete a move:

1) The V-bearing design limits the maximum acceleration, as high accelerations destabilize the carriage by inducing a rotation which lifts the carriage out of one of the bearings, depending on the mass distribution of the carriage. This will change the trajectory of ink drops fired from the ink cartridge, and the resulting drop placement errors will result in diminished PQ. In addition, if the rotation is excessive, there will be a large reduction of acoustic quality as the carriage slams up and down between hard stops on the bearings from move to move.
2) The maximum carriage speed at which reliable printing can occur is limited by two factors. First, the data transmission rate to the ink cartridges must not be exceeded, or image stretching will occur due to print data arriving at the cartridge too late to be placed in the desired position. Second, the fluid dynamics of refilling the ink firing chambers can cause color hue shifts due to ink drop size variation.

These constraints place limits on the maximum acceleration and velocity of the carriage trajectory. It is therefore important that the overshoot of these signals be minimized so that the average values can be kept as close as possible to the maximum allowed values.

### B. Economic Constraints

The economic constraints placed on consumer products such as HP's personal ink jet printers and multifunction devices are severe. The market pressures are relentless; adding cost without adding value can have major ramifications on the fiscal health of the company. At production volumes in excess of two million units per month, small increases in HP's direct material cost can reduce corporate profits by millions of dollars a year.

Because of the economic constraints, mechanical part changes require a strict cost to benefit ratio evaluation. Fortunately, the rapidly decreasing cost of run time computation has afforded the flexibility to trade off simpler, cheaper mechanical parts for more complex control algorithms. This trend is expected to continue, increasing the value of the control systems development community.

One very important manifestation of this tradeoff is the motor technology in use in HP's ink jet print platforms. Low cost, permanent magnet brushed DC motors are used because they are produced in volumes of hundreds of millions of units per year. This provides commodity pricing which in turn yields a price to performance ratio far beyond that of any other motor technology. Unfortunately, these motors do have some drawbacks, as will be discussed later. It is exactly this type of situation where the benefits of control algorithms enabling lower direct material cost can prove to be so beneficial.

### C. Computational Constraints

HP's personal ink jet printing platforms utilize a common commercially available embedded processor core. This processor has limited additional DSP hardware such as multiply and accumulate and saturating math. However, there is no floating point hardware. Thus to efficiently utilize the CPU, all run time algorithms must be implemented with integer math.

### D. Robustness Issues

While technically not a constraint, the robustness requirements for the control system will place limits on achievable performance of any algorithm. There are several major sources of variation in the system:

1) The production volume required to fulfill market demand requires the use of high volume manufacturing processes. The majority of the mechanical elements in the print mechanism are either injection molded polymer or stamped and formed sheet metal. These processes produce parts with significan dimensional variation. This variation tends manifest itself in frictional variation due to sliding part interferences.
2) The specified life of most of HP's print mechanisms is typically between 30,000 and 60,000 pages. During this life there will be significant wear on any moving mechanical parts. This will affect both friction and fit, which may lead to dead zones in the control system. Also, the printing process generates a fog of ink aerosol which tends to coat the entire interior of the print mechanism, increasing friction everywhere.
3) HP's personal print mechanisms are designed for usage in environmental conditions that typically range from 15°C to 35°C in temperature and 5% to 95% humidity. This will affect energy conversion efficiency of the motor, as well as the viscosity of lubricants.
4) Carriage mass varies considerably due to the mass of ink delivered while printing.
5) Print media drive friction varies greatly because of the different thicknesses and surface textures of various medias.

## V. Control System Challenges

The proceeding sections offered a host of challenges for developing a competitive ink jet print engine by providing the design goals and constraints. This section presents some specific challenges due to system disturbances and nonlinear behaviors that have proven to be particularly difficult to deal with. These behaviors tend to have a large affect on system performance. Of course, solutions to the problems put forth below must be solved within the context of all of the previously presented performance goals and design constraints.

### A. Non-Ideal Torque Generation

The first class of control system problems stems from the type of motor used for motion control in HP's ink jet printer mechanisms. Low cost permanent magnet DC motors are far from ideal torque generation devices. In addition to the manufacturing variation, these motors produce periodic disturbances which can cause issues resulting in reduced PQ and reduced performance.

The torque disturbances are intrinsic to the construction of permanent magnet DC motors. First, in order to wind copper on the rotor core, slots are required in the steel laminate stack that forms the rotor. These slots interrupt the reluctance path of the steel core which results in a torque distrubance as a function of angular position. Second, the mechanical commutation of the motor causes hard switching of the inductance of the winding, causing current spikes and a resulting torque disturbance.

This class of disturbance causes three problems for printer performance:

1) General motion trajectory problems. The torque disturbances make it more difficult to track the desired acceleration and velocity profile. The typical solution is to trade performance for robustness.
2) High quality printing requires very precise print media stopping accuracy. The current solution for producing the required accuracy in the presence of the torque disturbances is a combination of high gain control, low performance moves and a variety of heuristics which attempt to identify and counteract known non-ideal behaviors.
3) Torque disturbances can excite structural resonances in the system. This may lead to acoustical problems or dot placement errors resulting in poor PQ. Typical solutions have been in the mechanical realm, thereby increasing the cost of the product. In addition, the PQ issues show up late in the design cycle, after the more egregious PQ issues have been resolved, but often too late to fully address with mechanical changes due to production tooling schedule requirements.

While it has been possible to eliminate velocity ripple for systems at a steady state velocity, this solution has only been effective in addressing acoustical defects. Typically, the other issues presented will occur during acceleration and deceleration, when the frequency of the disturbance is changing with the motor speed. Also, for high speed moves, a significant portion of the overall move time is spent with a non-constant velocity. A successful solution will allow the active cancellation of the disturbance torque over a wide range of operating points as well as a dynamically changing operating point.

### B. Friction

The second class of problems is a general challenge for many mechanical control systems: friction. In general, friction is reduced as much as possible by using self lubricating polymer resins, high quality sheet metal surfaces for sliding and additional lubricants. However, friction can increase substantially over the life of the printer. This is due to part wear and lubricant performance degradation caused by contamination and migration away from the contact surfaces.

Friction affects performance in two ways:

1) Reduction in ability to follow desired motion trajectories. Friction is a disturbance force that must be counteracted by the control system. In general this requires trading performance for robustness. Controller complexity is also increased, as ad hoc methods are used to try to break free from static friction quickly. Another set of ad hoc methods are used to estimate and reduce both system and controller windup due to friction and avoid the resulting acceleration and velocity overshoot.
2) Paper axis stopping accuracy control is very difficult. Care must be taken to avoid limit cycling and to avoid opening the backlash of the paper drive gear train. In general this means a very slow approach to the target.

A successful solution will provide for the online estimation and cancellation of friction forces. It will also be robust or adapt to friction forces that vary over the life of a print mechanism.

### C. Acceleration Control

As previously presented, the carriage system V-bearings impart a unique design constraint in that there is a hard limit on allowed acceleration. If acceleration exceeds the limit, both PQ and acoustic quality of the printing process are greatly diminished. To further complicate the problem, the only feedback currently in use is the optical encoder. Thus acceleration feedback is only possible through double differentiation of the position signal. The quantization noise and phase lag of this signal render it largely ineffective for direct control of acceleration. The optical encoder is required for the printing process, and can not be eliminated. Current pricing for acceleration sensors has not provided a viable cost to benefit ratio.

The current solution for dealing with acceleration control is to reduce performance such that the absolute accelerations generated by the control system are below the acceleration limits. This yields average accelerations which are typically 30% below the maximum values, which greatly reduces printer performance.

A successful solution will provide much tighter control of the acceleration signal, allowing for the average value to be much closer to the maximum allowed value.

### D. Mechanical Dead Zones

All of the print media mechanical drives and several of the carriage mechanical drives have a mechanical dead zone. For the media drives this is the common gear train backlash problem. For some of the carriage systems, the drive belt is not directly attached to the carriage, but to a separate body that slides on the rod. This body then contacts the carriage. Clearances required for mechanical tolerances generate a dead zone in the carriage drive.

These dead zones place a hard non-linearity in the plant whenever the direction of motion is reversed. During printing, this is typically not an issue for the print media control system. However, the carriage direction is reversed for every print sweep. As such, the dead zone can greatly affect the performance of the system.

A successful solution of the backlash issues would provide an estimate of and compensation for the backlash region. The size of this region will be unique to each print mechanism.

## VI. Conclusions

This paper has presented an outline of many of the control systems challenges facing Hewlett-Packard in developing market leading ink jet print mechanisms. System architecture, design goals, design constraints and control system challenges have all been presented. It is hoped that this information can serve as a basis to create interest in solving these problems in a real world application.