Liquid Temperature Control for a Hydraulic Turning Machine

Jih-Jenn Huang and Daniel B. DeBra

The Stanford’s Quiet Hydraulic precision lathe was designed to use an exclusively hydraulic approach and equipped with an open liquid circulation system. By using a temperature-controlled liquid for a liquid shower, as well as for machine actuation, a uniform temperature environment can easily be maintained and the machining accuracy level can be assured. The liquid temperature is regulated by a commercially available cross-flow type heat exchanger. Due to the inherent time-varying and long time-delay characteristics, regulation of liquid temperature variation at the shower point down to m°C level is a very challenging problem. Successive feedback loops with Smith predictor and disturbance feedforward are implemented to regulate both the heat exchanger outlet and shower point temperature. Satisfactory long duration control results are obtained through this approach. In order to extend system bandwidth, the use of a Smith predictor with intentional temporal mismatch has been studied. It is found that the system performance can be improved by introducing an intentional mismatch for certain systems. The results are also verified by experimental observations.

Introduction

It is a well-developed concept that temperature variations will introduce dimensional uncertainties in a machining or measurement process. Consider a machine tool which is designed to have a dimensional length on the order of 1 m and a thermal expansion coefficient of the material that is on the order of about 10 µ-strain°C. When temperature variation is only 1 m°C, the machine tool will experience a dimensional change as large as 10 nm. This error is probably the maximum a machine designer is willing to allot to the thermal effects for a machine designed to have a surface finish accuracy on the order of 25 nm [1]. Thermal errors are the principal limitations of any ultra-precision machine, and a temperature control system is necessary for this precision level.

Fig. 1 shows the simplified machine construction of the Stanford’s Quiet Hydraulic precision machine. It was designed to use exclusively hydraulic actuation and equipped with an open liquid circulation system. The main research motivation is to take full advantage of the thermal capability of liquid shower and hydraulic systems, and it has been used as a testbed for novel sensing techniques and control applications. This machine is also used to demonstrate that a hydraulic approach is a good potential candidate for precision machining. Some former research results have made significant contributions to meet the research goal [5, 11-13].

The machine is composed of three major function blocks, which include the temperature control system, the pumping system, and the actuation system. The circulation oil is first pumped by the main boost pump, and passes through the temperature control system to remove oil temperature variations. The temperature-controlled liquid is then sent to the pumping system to increase oil pressure, and flows through the oil pipes (about 30 ~ 40 m in length) to the machine base for actuation. The exit liquid at the machine base and shower point is then collected back to the tank, and resumes the next cycle. The actuation system and oil tank are installed in a separate room to isolate them from the heat and noise coming from the pumping system. Fig. 2 is a photograph of the hardware setup of the temperature control system. A heat exchanger is installed at the bottom with oil pipes connected to the inlet and outlet port of the heat exchanger. Building chilled water is used as the heat sink, and guided by water pipes to pass through the heat exchanger. A servovalve is used to regulate the chilled water flow rate for oil temperature regulation, and

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Huang is a research engineer in the Chung-Shan Institute of Science and Technology, Taiwan. Email: jj_huang@msn.com. DeBra is an emeritus professor in the Department of Aeronautics and Astronautics, Stanford University, CA 94305. Email: ddeb@sunvalley.stanford.edu. The authors acknowledge with appreciation the support for this research supplied by the Republic of China at Taiwan and the National Science Foundation under Strategic Manufacturing Initiative grant NSF DDM-8914232. A version of the article was presented at the 5th IEEE International Conference on Control Applications, Dearborn, MI, Sept. 15-18, 1996.

Figure 1: Simplified block diagram of the Quiet Hydraulic precision machine.

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Water Pump
Heater
Servovalve
Heat Exchanger

Fig. 2. Photograph of the temperature control system.

A heater is used to increase the water temperature change to excite the model dynamics for model parameter estimation. There is also a water pump installed at the chilled water inlet to increase the pressure difference between the chilled water inlet and return so that more available water flow rate can be obtained.

As seen from Fig. 1, there are two feedback loops implemented for the temperature control system. One is the inner loop, which regulates the heat exchanger outlet temperature, and the other is the outer loop, which regulates the shower point temperature. The inner loop uses building chilled water as the heat sink and regulates oil temperature by changing the water flow rate. The outer loop uses the heat exchanger outlet temperature change as the driving force to regulate the shower point temperature. The purpose of the temperature control system is to regulate liquid temperature at the shower point down to m°C level to assure machining accuracy.

Previous Work

Most of the liquid temperature control application experience has been obtained at the LLNL (Lawrence Livermore National Laboratory). Roblee [2], Brown, et al. [3], and DeBra, et al. [4] have reported good control results by using multiple feedback loops with PI or PID controller to regulate the liquid shower point temperature. Some special attention has been paid to the hardware modifications in order to reduce the external temperature disturbances and the sensing circuit noises.

At Stanford, Chou [5] has developed a systematic approach through experimental and theoretical studies, and used a software approach to compensate for the disturbances. PI control was also used to regulate the liquid temperature, and combined with disturbance model feedforward to pre-condition large temperature disturbances. One control limitation noticed was that there is a residual fluctuation in temperature due to the variability of the heat transfer coefficient internal to the heat exchanger. However, less attention was paid to the management of long time-delay effects inherent in the system from the previous research results.

As discussed in Roblee's paper [2], the thermal response time of a machine has a great impact on the temperature control system. It determines the frequency range over which the control system must perform. This implies that the required temperature stability of the circulation liquid is frequency dependent, with larger and higher frequency fluctuations being tolerable. Motivated by the need to increase system bandwidth and reduce the long time-delay effects inherent in the system, the Smith predictor [6] is chosen to solve the problem. This article discusses the liquid temperature control implementation for the Stanford's Quiet Hydraulic precision machine and the tests of control feasibility and effectiveness.

Model Construction and Estimation

As seen in the photograph of temperature control hardware setup shown in Fig. 2, a commercially available cross-flow type heat exchanger is used as the main control component to regulate the inner loop liquid outlet temperature. Due to the time varying, distributed parameter, and long time-delay characteristics of the heat exchanger, it is difficult to model. Chou [5] has proposed a heat exchanger model which considers the input and output relationships as shown in Fig. 3. Heuristically, there are four factors that will affect the heat exchanger outlet temperature, which include the inlet oil temperature, the inlet oil flow rate, the inlet water temperature, and the inlet water flow rate. As the inlet oil flow comes from the boost pump, which is a constant displacement hydraulic pump, the oil flow rate can be regarded as a constant with negligible small variations; thus this factor can be neglected from modeling. The inlet oil comes from the oil tank, which contains about 600 gallons of oil. When the overall system has reached the thermal equilibrium condition, the oil tank will filter out major temperature surges and maintain the oil temperature variation on the order of about a couple tens of m°C. This varia-

![Fig. 3. Model block diagram of liquid temperature control system.](image)

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tion level is relatively small when compared with the water temperature variations (4-5 °C maximum, daily), and can be compensated by feedback control; thus the oil inlet temperature variation is neglected in this study. There are only two dominant factors that will be considered in the heat exchanger modeling, which are the inlet chilled water temperature change and the water flow rate. Because the heat exchanger is more sensitive to flow rate changes, so the liquid temperature is regulated by controlling the water flow rate through a proportional servovalve. The voltage signal sent to the electronic driver of servovalve is regarded as the control input of heat exchanger. Both the heat exchanger plant and the water disturbance model are described as a first-order linear transfer function plus a pure time-delay.

In order to control the shower point temperature, the outer loop plant dynamics have to be considered. The outer loop plant includes long pipelines (about 30-40 meters long), different pumping sources, and liquid mixing at the machine shower point. The theoretical model of the outer loop will contain distributed parameters and is not convenient for control purpose. Because the outer loop is basically a slow thermal process, its output response due to a change in the heat exchanger outlet temperature can also be described by a simple lumped first-order transfer function with a pure transport lag to capture its basic characteristic. Fig. 3 shows the open loop block diagram of the whole temperature control system, which includes both the inner-loop and outer-loop models. This model block diagram has a very clear physical perspective and decoupled property for control purpose.

Step commands are used extensively for model estimation, and the model parameters are estimated by least square fit. Table 1 lists the nominal values of the estimated model parameters. According to the data, it is worth noting that the total delay time for inner loop control voltage signal to show its effect on the shower point temperature takes about two minutes. This is a very long delay time that will constrain system bandwidth and stability range. In order to obtain an effective controller design and good system response, the long time delay effects have to be compensated through control methodology. The Smith predictor is chosen to achieve the purpose and will be discussed in the following sections.

**Feedforward Controller Design**

There are two major disturbance sources come from the environment: one is room temperature variation and the other is the chilled water temperature variation. Fig. 4 shows the measurement of the environment temperature disturbances. These data were taken for two consecutive days during April 1996, and is representative to show the variation range of the disturbances.

From the curves shown in Fig. 4, it is obvious that the room temperature is controlled by an on/off controller, because the temperature history during the day shows limit cycle oscillations. The oscillation frequency is estimated at about 2 cycles/hour, and the amplitude varies between ±250 °C. During the night, the laboratory shuts off air conditioning, so that the temperature behaves like an exponential decay. The same temperature measurement result repeats on the second day. As the room temperature varies between 21 ± 2 °C all year long, it will bring dimensional uncertainties to the machine tool. This problem can be solved by using oil shower, as the shower oil can block out the effects of room temperature variations and reduce machining errors due to the generated heat.

The other disturbance source is the water temperature variation. As seen from the curve shown in Fig. 4, the chilled water temperature shows random variation range between about 5 to 10 °C, and the maximum water change rate is about 6 °C/sec. This variation range is large enough to cause temperature variations of the circulation oil. feedforward control is a very useful method for dealing with the measurable disturbance. Refer to the model shown in Fig. 5 and follow Chou's work [5], the water temperature disturbance can be compensated by satisfying the following condition:

\[ \delta T_c G_w(s) + \delta T_c F_w(s) G_w(s) = 0 \]  

The equivalent feedforward transfer function can be written as:

<table>
<thead>
<tr>
<th>Table 1. Summary of Model Estimation Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger plant, ( G_h(s) )</td>
</tr>
<tr>
<td>Time constant, ( \alpha )</td>
</tr>
<tr>
<td>DC gain, ( k )</td>
</tr>
<tr>
<td>Time delay, ( T )</td>
</tr>
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Note: Assume the form of model transfer functions is defined as \( G(s) = \frac{k}{\alpha s + 1} e^{-aT} \).
Figure 5 shows the feedforward control result. At time point $t_1$, the sensor has detected a coming temperature disturbance, therefore the controller starts to send out appropriate additional control effort at time point $t_2$ to cancel the coming disturbance effect. After the control signal has passed through the dynamics of heat exchanger to time point $t_3$, the added feedforward control is able to cancel the effect of water temperature disturbance and let the outlet temperature remain disturbance free.

**Design of Successive Feedback Loops**

Smith's control scheme [6] is the most frequently used method for controlling systems with excessive long time delay. It has classically employed a model of the plant characterized by a linear transfer function and time delay. The Smith predictor uses the model to simulate both the delayed and undelayed state of the plant, and uses the delayed state to cancel the real plant output and the undelayed state for feedback control calculation. Fig. 7 shows the block diagram of the Smith predictor, and the corresponding transfer function can be written as

$$\frac{\delta T_r(s)}{\delta T_{mp}(s)} = \frac{C(s)G_p(s)e^{-\tau_p}}{1+C(s)G_p(s) + C(s)[G_p(s)e^{-\tau_p} - G_r(s)e^{-\tau_r}]}$$

where the subscript $p$ represents the plant, the subscript $q$ represents the model, and $C(s)$ represents the compensator which is chosen as PI control in this study. If model parameters match the real plant, i.e., $G_p(s) = G_r(s)$ and $\tau_p = \tau_r$, the above transfer function can be simplified to

$$\frac{\delta T_r(s)}{\delta T_{mp}(s)} = \frac{C(s)G_p(s)}{1+C(s)G_p(s)} e^{-\tau_r}$$

which offers an attractive feature by excluding time-delay from the control loop, and converts the control design to a delay-free problem. Intuitively, the parameter matched condition should have better performance.

According to the model estimation results summarized in Table 1, the liquid temperature control system has faster inner-loop dynamics and slower outer-loop dynamics. It is necessary to implement at least two control feedback loops, so that the faster inner loop can quickly filter out the higher frequencies and larger liquid temperature surges and obtain a liquid flow with quieter temperature variations; therefore a uniform temperature environment can be maintained at the shower point. The block diagram of the implemented successive feedback loops of the liquid temperature control system is shown in Fig. 8. Due to the different dynamic range of the inner and outer loop, a different sampling rate is chosen for each loop. Five hertz is chosen for the inner loop, and one hertz for the outer loop.

The Smith predictor, combined with PI control, has been implemented for both the inner and outer feedback loop. The inner loop includes an additional water temperature feedforward control for disturbance rejection. Care must be taken for the inner-loop Smith predictor implementation. Due to the inclusion of feedforward control, the disturbance effect of chilled water temperature variation can be excluded from the heat exchanger outlet oil temperature, so that the outlet oil temperature shows no information of the disturbance signal. Therefore, the corresponding control input of the inner-loop predictor has to be the

\[ F_w(s) = \frac{G_w(s)}{G_r(s)} = \frac{k_w}{k_r} \frac{a_r s + 1}{a_w s + 1} e^{-\tau_w}\]

where the subscript $w$ represents the water disturbance model, and the subscript $e$ represents heat exchanger plant. From the above equation, it is obvious that the causal condition, $T_w - T_e > 0$, has to be satisfied for the control to be effective. Because the time for water disturbance to show its effect on the heat exchanger outlet temperature is about 12 sec longer than control voltage signal, feedforward control can be applied in advance to pre-compensate for the coming disturbance input.
The liquid temperature control problem for the Quiet Hydraulic precision machine is summarized as follows: the purpose of the liquid temperature control is to regulate the oil temperature variation level to the order of 1 m°C at the shower point, in the presence of a large chilled water temperature disturbance which is about 5,000 times as large while restricted by a delay time as large as 120 sec. Successive feedback loops with model disturbance feedforward, PI control and the Smith predictor are used to achieve this purpose.

Fig. 9 shows the long duration control result at the shower point. The implemented successive feedback loops are able to regulate the liquid temperature at the shower point to fall within ±3.6 m°C (±2σ) for frequencies of disturbances less than 0.001 Hz. Due to the oil mixing at oil tank to filter out large temperature surges of the circulation liquid, and the appropriate thermal capacity offered by the chilled water and the heat exchanger, the controller is able to maintain the system to stay at thermal equilibrium condition. However, as the room temperature measurement shown in Fig. 4 shows limit cycle oscillations with an amplitude as large as ±250 m°C, this will unavoidably impose low frequency (approximately 0.001 Hz) temperature variations on the long duration temperature regulation results.

Temporal Mismatched Smith Predictor

Observations Through Transient Responses

As mentioned in the previous section, the parameter matched Smith predictor should offer better system performance by intuition, since the parameter matched Smith predictor offers a delay-free design. Fig. 10 shows the transient responses of the inner-loop control results. The solid lines are the control results of the model matched Smith predictor, and the dashed lines are the results of the pure refined PI tuning. One can see that the Smith predictor is able to recognize a large error at the very beginning and put in corresponding control effort to obtain faster response without saturating the control. This result is consistent with the intuition about the design of Smith predictor. The settling time of Smith predictor controlled system is about 40 sec faster than the one controlled by refined PI tuning. This result is very encouraging.
Applying a similar approach to the outer loop, the corresponding results are totally different from the ones of inner loop. The transient response controlled by the model matched Smith predictor shown in Fig. 11 becomes unexpectedly sluggish. No matter how hard one tries to come up with a good estimated model, the response is very sluggish and shows a long settling time. The dotted control history in Fig. 11(b) shows that although the controller is able to tell a large difference at the very beginning and put in a larger control effort to accelerate the transient, the predictor is unable to generate more error signal to drive the response due to the matched model, and results in an unexpectedly slow response. The settling time of the matched Smith predictor controlled system is about 17 minutes slower than the one controlled by the refined PI tuning. However, if we intentionally introduce a temporal mismatch to the outer loop by reducing the model delay from 120 sec to an arbitrary smaller value, for example 35 sec, the system response can be effectively improved and the settling time difference between the matched and mismatched case is as large as 20 minutes.

The above experimental results are very interesting and counter-intuitive, but questions will arise from these observations: Why are the control results different between the inner and outer loop by use of the model matched Smith predictor? And how can one use temporal mismatch to improve system response?

Theoretical Background
Following Marshall and his co-workers’ theoretical results [8-10] and adapting them to fit the liquid temperature control problem, the reasons for transient response differences through temporal mismatch can be obtained.

Assume a SISO system which contains a single time delay and is driven by a unit step command input, the Laplace transform of its error function, $e(t)$, can be written as

$$e(s) = \frac{Q(s) + S(s)\eta}{P(s) + R(s)\eta}$$

where $\eta = e^{-\tau}; P(s), Q(s), R(s),$ and $S(s)$ are polynomials of finite degrees in $s$ and real coefficients. The degree of $P(s)$ is assumed to be strictly greater than the other polynomials to simplify the derivations. This assumption is also generally true for cases of practical interest. The analytical method is to use the infinite time integration of the quadratic error function as system’s performance index and the Parseval’s theorem to carry out the integration in complex variable domain.

The technique for carrying out the complex domain integration is to separate the integrand into two parts, and each part contains poles of either $E(s)$ or $E(-s)$ exclusively. The integration then becomes finding the summation of residues at finite pole locations in either the left or right half of the $s$-plane. By using the symmetric properties of the root locations and the partial fraction expansion, an alternative form of the performance index integration can be derived as

$$J = \int_{0}^{\infty} e^2(t)dt = -\sum_{h.p.} \text{Residue} \left[ \frac{P(Q + S\bar{S}) - 2Q\bar{S}}{PP - RR} \right]$$

where the r.h.p. represents the right half plane poles and the upper bar represents the complex conjugate of the original transfer functions. Equation (6) is used to carry out the performance index integration. For more detailed information about the performance index integration can be found in [10].

Before carrying out the integration, there are two parameter normalization procedures that should be done. The first procedure is to normalize the parameter values of the original system relative to a base value. Because the parameter values of different systems might scatter in different ranges, they must be normalized so that system performance can be compared on the same basis. A general approach is to normalize the system parameters relative to its own plant delay time, so that the normalized plant delay time, $\tau_a = \tau$, is equal to unity and the other time-scaled parameters of system can be obtained correspondingly. The second procedure is to evaluate the performance index by excluding the quiet period due to time-delay from the integration and multi-
plying the index by a normalized gain, $K$, so that the gain factor can be simplified during integration. The final format of performance index becomes $KJ_p = KJ - KT$, where $sp$ represents the use of the Smith predictor.

According to the block diagram shown in Fig. 7, assume there exists only temporal mismatch between the plant and model. The zero of PI control is chosen according to pole-zero cancellation, and the proportional gain is chosen according to the refined PI tuning formulae listed in [7]. Assume the model delay is approximated by the Pade's first-order approximation to simplify the derivation. Let $\tau_s = \tau_p / \tau_n$ equal the temporal ratio between the model and plant delay time, and $K$ equation the overall gain factor after normalization; the closed form solution of the performance index integration is shown in Equation (7).

$$KJ_p = KJ_n + KJ_{\beta} - KT$$  \hspace{1cm} (7)$$

where

$$KJ_n = \frac{r^2\alpha^2 - (2 + 2rKt)^2}{2r^2\alpha^2} - \frac{r\alpha^2 - 2K\cosh[\alpha\tau] + r\alpha\sinh[\alpha\tau]}{2r^2\alpha^2 + 2r\tau + r\tau \cosh[\alpha\tau] - 2\sinh[\alpha\tau]}$$

$$KJ_{\beta} = \frac{r^2\beta^2 + (2 + 2rK\beta)^2}{2r^2\beta^2 + 2r\beta + r\beta \cosh[\beta\tau] - 2\sin[\beta\tau]}$$

$$\alpha = \left[ -S_s + \sqrt{S_s^2 + 16r^2(Kt)^2} \right]^{1/2}$$

$$\beta = \left[ S_s + \sqrt{S_s^2 + 16r^2(Kt)^2} \right]^{1/2}$$

$S_s = \left[ 3r^2(Kt)^2 + 8r(Kt) + 4 \right]$.

Fig. 12 shows the theoretical curves of performance index versus temporal ratio at different $K\tau$ values. The curves shown in Fig. 12 are drawn after another normalization process relative to a model matched theoretical value, 0.5. The curves demonstrate that system performance of the predictor type controlled system is actually a function of $K\tau$ value. When the system has a larger value of $K\tau$ (>1.5), the curves suggest the use of a model matched Smith predictor to get the best performance; however, the drawback is the high sensitivity to plant parameter variations. On the other hand, when the value of $K\tau$ is small (<0.75), the best model delay reduces to zero. When this extreme case occurs, the equivalent predictor type controller becomes a pure PI control.

This indicates that a pure PI control is the most appropriate controller for the system with lower values of $K\tau$. There is a gray area between the regions of pure PI control and the strictly matched Smith predictor ($0.75 \leq K\tau < 1.5$). System performance can be improved by introducing an appropriate temporal mismatch within this area; however, there is a trade-off that has to make between the improvement of system performance and the reduction of stability range. Fig. 12 offers a clear picture which demonstrates how system performance varies according to changes of the values of $K\tau$ and also the design guideline for using temporal mismatch to tune up system response.
Experimental Test Results for Temporal Mismatch

Fig. 13 shows the comparison between the theoretical and experimental results for both the inner and the outer loop. The normalized \(KT\) value of the inner loop is tuned as 1.05, and the \(KT\) value of the outer loop is tuned as 0.58. Due to the difference in \(KT\) values, it is not surprising that system performance behaves differently. The comparison between the inner loop theoretical and experimental results are shown in Fig. 13.a, which shows good consistency between the two approaches and the sensitivity due to the use of intentional temporal mismatches. Similarly in Fig. 13.b, the outer loop theoretical and experimental result are compared, which also demonstrates good consistency between the two approaches, and verifies the extreme case that the best performance occurs at using pure PI control for low \(KT\) value. The results shown in Figs. 12 and 13 explain the transient response differences observed in Fig. 10 and 11, and also offer a guideline for how to optimally introduce a temporal mismatch to the Smith predictor for tuning up system response. For slow thermal processes, a slight improvement of system transient response is obtained by introducing an appropriate temporal mismatch, and a tremendous time saving can easily be obtained. As for the 0.01 Hz bandwidth of the inner closed loop, the time saving of its transient response by optimally tuning the Smith predictor is on the order of about tens of seconds, while for the 0.001 Hz bandwidth of the outer closed loop, the time saving could be on the order of about tens of minutes.

Conclusion

The effectiveness of successive feedback loops with the Smith predictor and disturbance feedforward are applied and tested. A satisfactory long duration shower point temperature regulation result is obtained through this approach. We are able to regulate the liquid temperature at the shower point to a few m°C level for frequencies of disturbance less than 0.001 Hz, in the presence of a large chilled water temperature variation which is about 5°C while restricted by a delay time as large as 120 sec. The improvement of system performance by introducing appropriate temporal mismatch is also investigated by theoretical derivations and supplemented by experimental observations. The appropriate temporal mismatch is found to be determined based on the resulting \(KT\) value of the compensated system.

This article discusses only the temporal mismatch problem; however, apparently there are other parameter mismatches and the corresponding performance and stability problems need to be verified. As a system with a time-delay can be time-varying and have distributed parameters, there are inevitable parameter mismatches between the model and plant. The study of parameter mismatches and the performance improvements obtained by introducing parameter mismatches will find valuable use in both academic and real world applications.

References


Jih-Jenn Huang was born in Taiwan. He received the B.S. and M.S. degree from National Tsing-Hua University in power mechanical engineering, and the Ph.D. degree from Stanford University in Aeronautics and Astronautics with a Ph.D. minor in electrical engineering. He is currently a research engineer in the Chung-Shan Institute of Science and Technology at Taiwan, working on precision servo actuation systems. His research interests lie in the field of control analysis and design, hydraulic systems, and electromechanical systems.

Daniel B. DeBra is an Emeritus Professor with a joint appointment with Mechanical Engineering and the Aeronautics and Astronautics departments at Stanford University. He collaborates with the Stanford physicists on three projects: Gravity Probe-B (GP-B), Space Test of the Equivalence Principle (STEP), and the vibration isolation of a gravity wave antenna. These involve satellite control of attitude and translation and the development of instruments of extraordinary precision and accuracy. In GP-B, gyroscopes will be orbited and compared to stars to an accuracy of less than a milliarcsecond. In STEP, the orbital performance promises improvements of a million in testing the equivalence of inertial and gravitational mass. Professor DeBra's interests in precision engineering extend to manufacturing, where he has students developing "Quiet Hydraulics" capable of controlling diamond turning machines with enhanced temperature control.