## Foreword

The Duality Lathe is a unique accessory for Tormach's PCNC 1100 CNC mill. This document is an engineering overview of the development of the product and is presented to help potential customers determine whether the product is suitable to their needs.

As a design document, this is parallel to the mill engineering review[1] but differs in that this is somewhat less of a static engineering analysis and a bit more of a chronological development story. It's offered more like an extended blog. The purpose remains the same; we want to present some of the background and the thinking that lies behind the development of this unique product.

## Early Stages

### *Evolution of an Idea*

The evolution of the Duality Lathe concept began with thinking about the needs of an R&D workshop. A lathe and a mill are two of the most common tools in an inventor or entrepreneur's workshop. These are basic tools, largely due to the fundamental nature of machinery. Whether it's the world's smallest wrist watch, or a 1600 horsepower diesel engine, machinery generally includes a framework and, contained within, a series of rotating components. A mill is needed to cut the framework, while a lathe is needed to cut the rotating elements. This simple observation has a lot to say about the working relationship between a lathe and a mill. Because the rotating elements of a machine are generally held within the framework, the necessary lathe is smaller than the mill. While large machines are built with large tools, and small machines are built with small tools, the size relationship between the mill and lathe remains basically the same; the lathe is typically smaller than the mill.

This simple observation also sheds light on some of the frustration with the design compromise of a 3-in-1 machine, a common hobby grade machine tool. With a 3-in-1 machine, the tool carriage of a lathe serves double duty as the table of a mill. Essentially, it's a mill contained within a lathe. The nature of the design leads to a mill which is considerably smaller in capacity than the lathe, the opposite of the relationship naturally required.

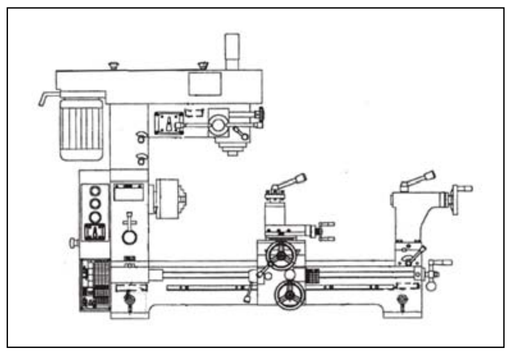

**Figure 1 - 3 in 1 machine**

Another important observation is the impact of CNC capability upon the utility of a machine tool. Creation of contoured edges and 3 dimensional shapes on a milling machine is only practical with CNC. The geometry is not simply a matter of making parts look nice, it is often essential to fluid flow, strength/weight ratios, stress management, and other critical factors of design performance. This makes the difference between a manual mill and a CNC mill dramatic. For a mill, CNC opens a world of design capability that a manual mill simply cannot deliver. CNC on the lathe is very different. Small radius corners are created by the radius of the tool. Large radius corners, tapered shanks, or contours on outside dimensions are rarely needed. When looking to make a few parts for a prototype design the machinist will rarely go to a CNC lathe, a manual lathe works just fine. For lathe work, CNC becomes an enabling technology not for prototypes but when it comes to quantity production.

---

[1] http://www.tormach.com/document_library/TD30204_DesignAnalysis.pdf

Quantity does not have to be large to be important. Consider a typical small device; it might have a milled case, a cover, a couple rotating shafts, and then a dozen specialized screws. It's not hard to cut a screw, but nobody wants to make a dozen of them. The conclusion here is that CNC is pivotal to a mill; fundamental to what can be done with the tool, but CNC is only a convenient time saving addition to a lathe.

Musing on the ideas above resulted in the Duality Lathe idea; why not turn the 3-in-1 concept inside out? Instead of putting a mill inside of a lathe, put a lathe inside of a mill. By making the lathe an accessory device that fits within the envelope of the mill, the expensive motion control capability of the mill serves double duty. By making the lathe dismountable, the mill suffers no compromise in design as there is nothing left behind to get in the way. If the lathe frame has its own tool carriage then it also serves a dual function, as both CNC lathe when working within the framework of the mill and manual lathe when outside the mill. With the 3-in-1 machine concept the lathe spindle centerline cannot move relative to the milling spindle. With the Duality Lathe concept, the entire lathe moves relative to the mill spindle. This allows the lathe to act as a fixture for the turned work piece when the system is used as a mill.

The fundamental idea is the embodiment of the phrase *"The whole is more than the sum of the parts"*. The parts were only two: a small manual lathe and a CNC mill. The whole was the availability of three machines, a small lathe, a CNC mill, and a CNC lathe with active tooling & integral mill. The big question was whether or not the CNC lathe functionality really worked, or if it was too gimmicky to be effective. Some preliminary testing was in order.

## *Prototype testing*

The initial testing involved a commonly available bench top lathe, often called a mini-lathe. We planned for several basic tests:

| | |
|---|---|
| Cut Off | Facing |
| Turning | Taper |
| Ball End Turning | Threading |

The initial tests surprised everyone. We had expected some things to work, but we also expected a few problems. Instead, every function worked perfectly on the first run. One of the aspects we had expected was an improved cut and a dramatically lower tendency for lathe chatter. It's pretty well understood the primary source for lathe chatter is the stiffness of the lathe tool post and carriage. The small lathe we used had a total weight of about 85 lbs and the tool post and carriage assembly weighed just a few ounces. In the CNC configuration, the lathe tools were solidly mounted to the PCNC 1100 spindle cartridge. The spindle head itself weighs more than 200 lbs. With the lathe tool solidly attached to 200 lbs of iron lathe chatter can still happen, but it will never happen at the tool post and it will only occur under the most severe conditions.

The lathe ran under its own spindle with a manual speed control. Threading requires synchronization between the axis motion and the spindle rotation. This was accomplished by using a once per revolution sensor on the lathe spindle. The revolution sensor was input to the accessory input of the mill, and the mill was programmed to act as a slave to spindle speed. The system worked so well that we were able to do a restart on the thread cutting. After finishing a threading routine we found we had not programmed quite deep enough and the nut wouldn't fit. We modified the program a bit and it restarted, dropping perfectly into the original thread. Prototype testing went so well, it was clear that we had to develop the concept further.

One interesting aspect was the utility of simultaneous CNC and manual operations. We had thought of it as two modes: CNC when mounted on the mill and manual when sitting on the workbench. The fact of the matter is the manual tool carriage is autonomous to the CNC tool post and is still available when the lathe is in CNC mode, mounted on the mill. When buying their first CNC lathe people are often concerned about the ability to use it in manual mode. With the Duality Lathe concept this is not only true, it's available in two flavors. There are manual operations of the CNC system in the form of an electronic hand wheel or keyboard controls, and then there is the conventional manual controls, operating a different tool, a different tool post, and with independent mechanical hand wheels.

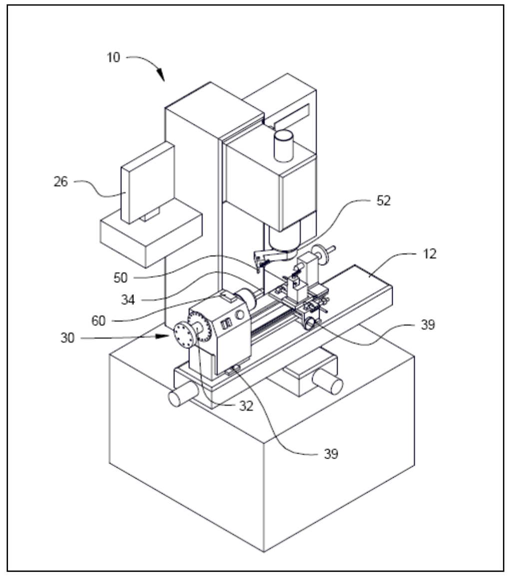


**Figure 2 - Patent Application Sketch**

One of the first things we did after initial testing was to proceed with a patent application. The patent search revealed someone had tried using lathe components on a CNC mill (US Patent 4057893), but their approach incorporated a very flimsy tool post concept and totally missed the dual purpose idea, where the lathe could be kept intact and used as a manual lathe when off the mill.

## Continuing Development

### *Original versus Derivative*

At this point, we had a proven concept, but we were still a ways from a final design. The next logical question was whether the final product should be a derivative of an existing small lathe or a totally original design, optimized to the task. The other question is, of course, what is the optimized design? For a start, we considered what we might want in a dual purpose lathe:

- High Precision
- Rigidity
- Low Cost
- Full integration with mill, including spindle speed integration
- Threading capability
- Ability to use the lathe spindle as a 4$^{th}$ axis when running mill software
- Ease of use. Particularly it should be lightweight for easy removal or from the mill table and offer quick change over.
- Lathe tools should be interchangeable between manual and CNC tool posts

In contrast, we listed the inescapable compromises were inherent to the Duality Lathe concept. These are the issues that are really linked to the Duality Lathe concept and would exist no matter whether the end product was original or derivative:

- Size imbalance remains: In the 3-in-1 concept you end up with mill that is much smaller than the lathe. In the Duality Lathe concept, you end up with a lathe that is much smaller than the mill. This is better, but not optimum. The optimum situation, at least the situation that most workshops end up with, is a lathe only slightly smaller than the mill.
- Precision limitations: A general purpose mill is fine with precision on the order of 0.001". Higher precision is much more expensive and not commonly needed. Lathes are often involved with the creation of pieces that

are subject to a precision fit, such as a press fit on a bearing. It's common to call upon a lathe to deliver 0.0002" in diameter precision. The length axis of a lathe is much less demanding. Because the radius axis of the Duality Lathe would be provided by the Z axis of a mill, there is a fundamental mismatch in precision requirements between the lathe and the mill. While 0.001" is OK, it's not the spec that we would design a stand-alone lathe to.

- Swiss Army Knife Syndrome: While prototype tests showed the idea to be very effective, it would still require a couple minutes to convert between lathe and mill. There are always application limitations of multiple purpose tools (Swiss Army Knife) and this might not be the ultimate solution for someone who needed a CNC lathe on a daily basis.

With the list of features and compromises in hand we considered the question of a fully original design versus a derivative design. One of the major differences would be the integration of the electronics. A fully integrated system would have the lathe spindle speed under computer control. A lesser integration, and much less expensive, would have the spindle speed monitored, but not controlled. This would allow axis synchronization, as needed for thread cutting, but it would require manually setting the spindle speed.

Skimming over the details of that analysis, the conclusion was that the cost difference between an original design with full integration and a derivative design with partial integration would be a factor of 2x to 3x in cost. If we could manage to deliver a derivative design for something like $1000, a fully optimized original design would probably end up at near to $3000. In comparison, we felt that a ballpark cost for a conventional small CNC lathe would be something like $4000 to $4500. If you compare a conventional $4500 CNC lathe to a $3000 Duality Lathe, and then consider the compromises that are inherent to the Duality Lathe idea, it doesn't seem like such a great idea.

On the other hand, if you compare a $4500 CNC lathe to a $1000 Duality Lathe, the idea looks like a real winner, particularly for someone who only has an occasional need for a CNC lathe. The compromises inherent to the concept remain, but the capability offered would still be exceptional given the expected cost. The primary limitations would be manual speed control on the lathe spindle and the inability to work to .0002" accuracy.

## *Design Details*

***Base Model Selection:*** There are literally hundreds of manufactures of small lathes to choose from. The smaller models, those less than 60 lbs, were considered too flexible to be of much use. The larger models, those over 100 lbs, would be exceptionally difficult for most people to move around. The lathe had to be mobile to fit the Duality Lathe concept. This limited our available selection to a few dozen manufacturers, mainly from Germany, India, and China. One particular model, known as the Mini-Lathe, has become very popular with hobbyists in the USA and Europe. This is a small Chinese manufactured product, the same model we used for the early prototype testing. The generic model is sold under private label by a variety of discount tool importers. We purchased two more, each from a different discount tool importer, in order to check precision and consistency of manufacturing.

We found the fit and finish were generally acceptable. The critical tolerance for us was on the lathe spindle itself since that's the primary component that is shared between CNC and manual modes of operation. We used a Starrett Last Word indicator with 0.0001" graduations. What we found was a TIR (total indicated runout) of two of the lathes was not detectable, and the third was only 0.0001". This was surprising for a low cost hobby lathe.

We contacted the manufacturer directly and discussed the possibility of a custom variation of their little lathe. They were interested in working with Tormach and agreed to our stipulation of 100% on site quality control audit of the final QC inspection. It's common for the major discount tool distributors to perform inspections, but their inspections are typically limited to making sure the color is right, the labels are on straight, and machines mostly turn on without smoke being involved. Tormach has followed the policy of having an auditor on site, monitoring the final QC, and co-signing the inspection document that goes with each machine. As this would be a new supplier for us we wanted to be careful on the QC and continue with the policy we had been using on the mill itself.

***Tool Post Position:*** The position of the CNC lathe tool post was an important issue. It had implications on accuracy, tool design, and software interactions. The image to the right shows a tool post, tool, and work from the viewpoint of the tailstock. Since we wanted the CNC tool post to be able to co-exist with the manual tool post there were two reasonable positions, at 90 degrees and 180 degrees to the conventional manual tool post.
The image here shows the 180 degree position with a reverse direction of the lathe spindle as 'A'. The 90 degree position is either 'B' or 'C', depending on the rotation. Any of these three positions could have been selected for our design.

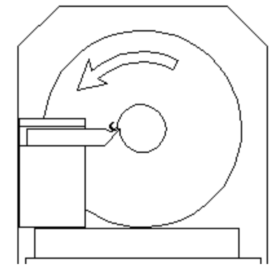

**Figure 3 - Standard Tool Post**

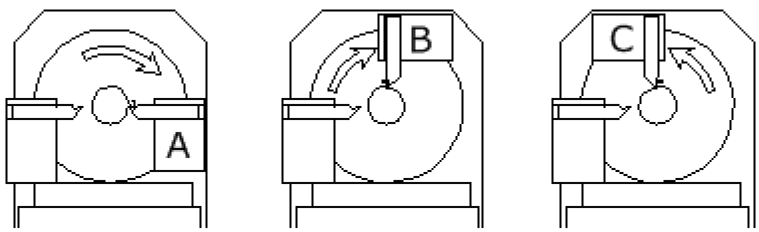


**Figure 4 - CNC Tool Post Alternatives**

In analyzing the alternatives we found that the introduced some difficulty for users in visualization in the A and B positions. Every CNC cut would be a mirror image of a manual cut, the operator would have to think backwards. The tools would also be reversed. What requires a left cutting tool in a manual operation will need a right cutting tool for CNC in the A or B positions.

Perhaps the most important consideration is the overall machine stiffness. Looking at the image to the right, testing stiffness in the vertical position showed a K value of 13,500 lbs/inch, while testing in the horizontal position showed 3200 lbs/inch. The increased stiffness against vertical forces comes largely from the fact that vertical forces put the mill's dovetails under compression, simply adding to the normal force from the weight of the table and lathe. The horizontal force is more difficult to resist because it puts a twisting force (moment) on the mill's dovetail slide. In terms of tool post position the A position tool post sees cutting diameter, the critical dimension, as subject to the lesser stiffness of horizontal forces and tool height.
In the B and C positions, cutting diameter will be more accurate because it relies on the improved stiffness of the vertical forces.

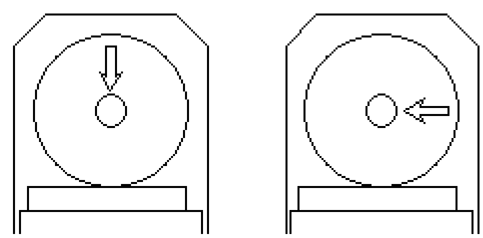

**Figure 5 - Force Directions**

Combining these factors it becomes clear that the C position is superior. It offers the greatest accuracy on cutting diameter, simple visualization, same turning direction, and allows tools to be interchanged with the conventional manual tool position.

***Quick Change:*** Interchangeable tooling and the tool table in a CNC controller are cornerstone assets of CNC. We knew from the start that we would want the ability to quickly change tools without the need to re-reference the machine.

There are two basic styles of tool posts, the piston lock and the wedge lock. The piston lock has a pin that forces against the tool holder, jamming it against the dovetail and locking it into position. It works well, but it locks it into whatever position it happens to have, whether right or wrong. The wedge style has one side of the dovetail moving out and down at the same time. It also locks the tool holder in place, but the sliding wedge will pull down the tool holder at the same time it locks. This ensures positive placement against the limit stop providing both a more repeatable and more rigid tool mount. The wedge style is significantly more expensive, but also more accurate, than the piston style.

Another alternative in design is aluminum versus steel. Despite the higher cost of material, aluminum is lower in cost due to the ease of machining. The lower rigidity of aluminum is not really significant in a very small tool holder, but the lower yield point makes it less durable. It's easy to get dings & dents in the precision sliding surfaces.

Tormach has a long relationship with Chris Wood of Little Machine Shop Inc; LMS was one of the early distributors for the Tormach Tooling System. Chris has built a business on supporting desktop machine tools and is very familiar with all variations of the mini lathe. Since Little Machine Shop offers 6 different brands of quick change tool holders that fit the mini lathe, we gave him a call and asked for his opinions on their relative merits. While each of the brands has a lot to offer, Chris felt that none of them represented the ultimate design. Furthermore, Chris had some well developed ideas on what the design should be. After comparing his ideas to our own and passing back and forth a few drawings, we came up with what we agreed would be the ultimate mini lathe quick change tool post. After manufacturing some prototypes and making a few adjustments in the design, we had the design we wanted. The final design had a steel body with precision ground surfaces and a sliding wedge style design. We found an independent manufacturer for the quick change tooling system, confirming the quality with a prototype run.

***Spindle Position Control:*** One of the unique attributes of the Duality Lathe is the ability to use the lathe spindle to hold a work piece while cutting with the mill, essentially acting as a mill $4^{th}$ axis. It would be convenient if we could use the lathe drive mechanism, designed for 2500 RPM, to also hold the spindle position against the high forces of milling, but that simply is not practical. Any mechanism to accomplish both high speed rotation for lathe turning and precision position control for milling would be larger, complex, and expensive. The alternative is an independent drive mechanism that can be clutched out, allowing the standard lathe spindle drive to be used in lathe mode, and the secondary drive mechanism to be used in $4^{th}$ axis mode. This approach allows the control system of the mill, designed for a conventional $4^{th}$ axis, to serve double duty as the lathe positional axis control.

Of course, the addition of precision positional control comes at a price, in weight, size, and just plain dollars. Dynamic position control allows the A axis rotation to be synchronized with X, Y, and Z motion while milling. This is required for things like engraving text over the surface of a cylinder or spiral fluting. More common tasks, like cutting a keyway slot or drilling through a turned work piece only require the spindle to be fixed in position. A simple spindle clamp will allow those functions, without the costly addition of a motorized drive system. If the spindle clamp were fitted with index divisions then simple indexing operations that didn't need high precision could also be accomplished, such as milling a hex head on the end of a turning.

With the simplicity of an indexable spindle clamp covering the majority of applications, and considering the complexity, cost, and weight of a motorized A axis drive, the conclusion was to have an indexable spindle clamp as a standard feature on every Duality Lathe. A motorized C axis drive for the lathe would be a dismountable accessory.

***Spindle Speed Sense & Display:*** The design decision to use manual speed control instead of computer controlled speed control does not make for any serious limitation as long as the spindle has a sensor that can pick up a position sense once per revolution. The CNC control system can pick up the signal and derive both instantaneous position and velocity of the spindle. Spindle speed is important because the surface speed of any cutting operation strongly affects surface finish and tool life. Most CAM programs will assist by specifying the desired spindle speed for an operation. It's stated in the G code program as the S word. The problem is that, for the sake of economy and simplicity, we decided that our controller would not be setting spindle speed. In order to minimize the impact of this we added a screen graphic to facilitate manual speed matching.

The graphic for speed matching has two sections, numbers and colors. The programmed spindle speed is displayed directly adjacent to the actual speed determined by the spindle sensor. When there is a large difference between the programmed spindle speed and the actual speed the colored graphic turns red. When they are close, they turn yellow. When the speed is very close it turns green.

With this information the system can operate the X and Z axis[2] in a slave mode where precise synchronization is required between X, Z and spindle rotation. This is what happens during thread cutting.

In order to run multiple passes on a thread cutting operation the control system needs to bring the tool into the spinning work multiple times. With each pass it must hit the work at exactly the right angle of rotation. Is this really possible with a once per revolution sensor? Let's look at the numbers. The computer can be set to 35,000hz for a motion update rate. This means it has the capability to act on position and velocity 35,000 times per second. If we try to do threading at a spindle speed of 600 RPM, we have 10 revolutions per second. With the update rate at 35,000 per second and the spindle at 10 per second, we have 3500 updates per revolution. In theory this means that the position of the spindle can be estimated at 1/3500$^{th}$ of a revolution, approximately 0.1 degrees.

While 0.1 degrees is certainly good enough to do threading, there is one limitation. The estimate of position of the spindle based on time assumes a constant spindle speed. If the spindle is decelerating as it is rotating there will be a small error involved and the thread will not be as accurate as we might like. Over any distance the thread will have the right pitch, but the quality of the thread can suffer. This can happen if the depth of cut per pass in threading is set too deep. If the load makes the spindle slow down as it enters the cut then the quality suffers. Our testing showed that this problem could occur, but we quickly learned to watch depth of cut and monitor spindle speed. As an aid to operation we developed a pseudo load sensing algorithm based on the only information available, the rotation sense. We created an on-screen display that showed real time variation between a filtered (long term average) spindle speed and the instantaneous spindle speed. Whenever the cutting tool dips into the work there will be some variation in spindle speed. During normal operations the variation is insignificant. If the cutting depth is too deep or the tool is dull, the speed variation will show up in the display, thus providing warning of potential synchronization issues and thread cutting quality.

## *Software support*

We have seen how the lathe can be used in a spectrum of modes ranging from it being a manual lathe, freestanding on the bench, to cutting a complex CAM generated part with multiple tools. There are two important modes in the middle of this spectrum. The first is manual operation using the mill CNC jogging controls in place of the lathe

---

[2] In a CNC lathe the left/right motion of the tool is referred to as Z axis motion, while in and out motion relative to the spindle centerline is referred to as X motion.

handwheels. The second is semi-automatic operation where one might wish to turn a bar down from say 1” to 7/8” with several passes.

Both these operations are useful when setting up a job to be turned by a CAM generated part program. It is standard practice to set the Z=0.0 position by a light facing cut on the end of the stock. In an R&D situation it is common to need to start with stock bigger that that actually required, but which is available in the stores, and to turn it down to the size expected by the part-program.

As the axes of the machine can be jogged and the positions are displayed by the DROs on the computer screen, then accurate jog machining can easily be performed on the lathe.

The semi-automatic operation, for example turning a length of stock down to size, is a sequence of standard steps and rather like the “Canned Cycles” available in G-code programming. The Duality software provides a selection of these cycles where the operation required is defined by filling in boxes on the computer screen. This combination of a visual data form and canned cycles gives the name VisiCycles.

The standard VisiCycles were designed to cover: facing, turning to size, chamfering and threading. Because an important use of them is in preparation for running a G-code program, they can be used without interfering with the program which stay loaded throughout.

The full power of the VisiCycle feature is easier to grasp by using it than by description but if you imagine it as offering intelligent cutting with digital stops for the carriage and cross-slide you will understand the semi-automatic operation that is available.

***Emergency Stop Integration:*** When the Duality Lathe operates as a CNC lathe it’s really a case of two machines acting as one. Just as the tool is about dive into the metal, that’s usually the instant when you realize that you missed the decimal point, entering 1” instead of 0.001”. This is not the time when you want to be thinking “Hmmm. Should I hit the red button on the lathe to stop the spindle, or should I hit the red button on the mill to stop the axis motion?” Incidents that call upon use of the E-stop button are sudden and sometimes unexpected, not when one should have to consider which red button to be reaching for.

The Duality Lathe has been designed for full integration of E-stop. This requires a minor conversion of the PCNC 1100 in order to conjoin the lathe E-stop with the mill. There is a cable between the mill and the lathe to integrate the E-stop systems when acting as a single unified machine. When the machines are run independently a special cap is placed over the integrated E-stop cable receptacles. This cap has an internal E-stop feedback jumper which allows independent operation.

## Project Completion

***Beta Prototype:*** With the majority of the detailed design decisions completed, we transferred drawings to the factory and arranged for a beta prototype to be made. The early testing was conceptual only. We didn’t have the spindle clamp, the tool post was improvised. We wanted to see the complete design. About 2 months later we visited the factory to inspect production facilities, review the beta prototype, and finalize details with the factory engineers. We found the spindle clamp mechanism worked well, but the alignment mechanism needed some changes. This is a system that allows for adjustment of the alignment of the lathe to the mill table. Once adjusted, it can be locked in place, allowing the lathe to removed and replaced while preserving the alignment. We also reviewed the quality control tests with the engineering staff. The Duality Lathe concept required an additional test procedure beyond what is normal for a lathe: checking the alignment of the lathe bed to the lathe feet. A conventional lathe only requires precision between various internal surfaces. Because the Duality Lathe is really a subcomponent of a larger system, it needs to be precisely aligned relative to the mill. Our testing process would check alignment relative to a large surface plate.

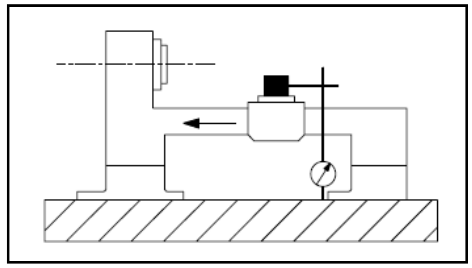

**Figure 6 – Parallelism of surface plate to longitudinal motion of carriage**

***Preproduction Model:*** With the mechanical and electrical details confirmed, we arranged for a preproduction model to be built. This would be the final test. We would be looking for confirming the packaging, color, label, and all details of the production model to be confirmed. The preproduction model was air freighted to our USA office late in 2007. Everything looked good and the design moved into production.

***Conclusion:*** We're excited about the value of the Duality Lathe, offering all the function of a small CNC lathe and more. It will be usable with whatever combination of manual and CNC programming is required yet is available at a fraction of the cost of a conventional CNC lathe. We have spent months working with the prototypes, thinking about the details, and considering the inevitable compromises that design decisions must resolve. Never the less, with something as unique and original as the Duality Lathe, engineering does not stop once the product begins shipping.

We have done our best, but we're expecting that the people who start using the product will come back to us with additional ideas. At this point it's a double edged sword for design engineers. As a new product goes to market and feedback begins, any designer is optimistically thinking "*I hope they like what we've done*", and at the same time there is trepidation, worrying that one of those user feedbacks which result in "*Damn, I should have thought of that myself*". It's all part of the process.