A New Kind of Parallel Mechanism Machine Tools with an Integrated Cartesian Guiding and Metrology Mechanism

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Abstract

A new kind of parallel mechanism machine called the CGT (Cartesian-Guided Tripod) for three-axis machining, CGP (Cartesian-Guided Pentapod) for five-axis machining, and CGH (Cartesian-Guided Hexapod) for six-axis positioning is presented on this paper. The CGT/CGP/CGH has two kinds of functional independent legs: the driving functional leg and the integrated Cartesian guiding/metrology functional leg. The platform displacements are guided and measured in Cartesian coordinate system using the integrated Cartesian guiding/metrology leg. A systematic comparison of the CGT's performance relative to conventional machine tools was conducted. This comparison includes the footprint, transmission ratio, static rigidity and dynamic stiffness, geometric error sensitivity, and servo-controlled contouring accuracy.

(key words: parallel kinematic mechanism, tripod, direct metrology loop, Cartesian guiding mechanism)

Introduction

The basic idea of the CGT/CGP/CGH is to separate the guiding and metrology functions from the driving function for every leg. The CGT/CGP/CGH has two kinds of separated and functional independent legs: the driving function leg and the integrated Cartesian guiding/metrology function leg (Fig.1). The number of driving function legs depends on the number of degrees of freedom (DOF). The integrated Cartesian guiding/metrology leg is purposed to guide and measure the platform motion in the Cartesian coordinate system. The integrated Cartesian guiding/metrology leg has the same DOF as the machine's Cartesian DOF. The separated driving function legs and integrated Cartesian guiding/metrology leg are parallel-linked to form the workspace for the CGT/CGP/CGH. Figure 2 shows the preliminary design drawings for the integrated Cartesian guiding/metrology leg and the assembled CGT for a three-axis machine tool application.

There is no real need for a six-axis machine (for multi-axis machining the sixth axis is redundant with spindle rotation) [1-4]. By adding two more driving legs and a universal joint, the CGT can easily be expanded into a five-axis CGP (Cartesian Guided Pentapod) without the redundant sixth axis (see Fig.3). A six-axis CGH (Cartesian Guided Hexapod) can be made in the same way by adding three more driving legs and a ball joint to the CGT.

Footprint Ratios

Table 1 lists and compares information on several well-designed high-speed machining centers gathered from the commercial market. Because there are so many axis arrangements for conventional machine tools, the configuration of each machine is also listed. The CGT has a Cartesian-axis-travel to floor-stand-length ratio of 1/5 ~ 1/6. Well-designed conventional machine tools in the commercial market have a ratio between 1/3 ~ 1/7. The reachable space of this CGT is slightly larger than a rectangular box. Therefore, the CGT has the same footprint quality as the conventional machines.

Table 1: Comparison of the footprint quality

	Brand	Machine Configuration	Workspace (mm)	Footprint (mm)	Travel/Floor
1	CGT	X/Y/ Z(moving column)	400x400x400	2600x2252x2332	1/5~1/6
2	A	X/Y/ Z(moving column)	600x450x400	2450x2500xN	1/5~1/6
3	B	X/Y/Z(moving column)	510x320x300	3200x1700x2370	1/5~1/7
5	C	Z(bed), X/Y(short column)	800x850x800	5200x4200x3200	1/4~1/6
6	D	X/Y(bed), Z(fixed bridge)	700x400x350	1860x2318x2587	1/3~1/7
7	E	X/Y(bed), Z(fixed column)	560x460x450	1800x2380xN	1/3~1/5
8	F	X/Y(bed), Z(fixed column)	700x420x410	2800x2800xN	1/4~1/6

Transmission Ratio

The transmission ratio analysis result is listed in the Table 2. The CGT driving mechanism is divided into two basic types: sliding leg and telescoping leg. The initial horizontal angle θ_o of the leg is measured when the platform is at the center of the working space, called the home position. The transmission ratio F_{Rq} is defined as the local-velocity/Cartesian-velocity. The same F_{Rq} value is also applicable to the acceleration ratio. From Table 2, the results show that the sliding leg CGT has a poorer transmission ratio than that for the telescoping CGT. In the current state of the conventional high-speed machine tools, the Cartesian velocity and acceleration can be more than 60m/min and 1.5g respectively. In that case, the sliding leg CGT will require a driving mechanism to perform a movement nearly 320 m/min and 7.9g for the θ_o=45^o case. This is a difficult and expansive task for the current ballscrew technology, even for linear motor technology. The telescoping leg CGT has a better transmission ratio value of 1.73. For the current commercially available ballscrew and servomotor technology, driving a 400kg mass at a motion of 120m/min and 4g is not difficult.

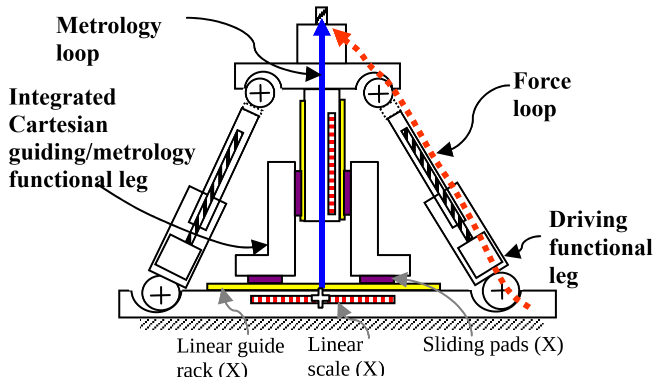
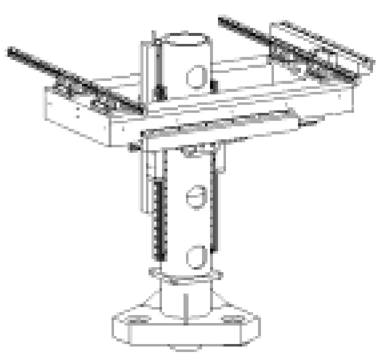
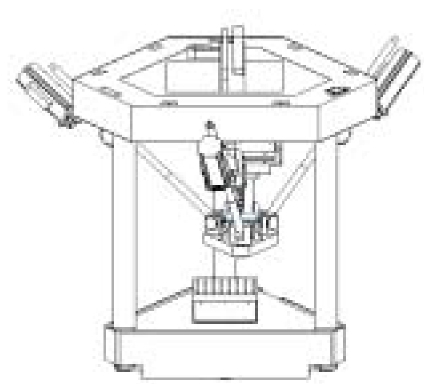


Fig. 1: Separated and independent functional legs of the CGT



a) The integrated Cartesian guiding/metrology functional leg for a three-axis machine tool



b) The assembled three-axis CGT

Fig.2: A preliminary design example of a three-axis CGT

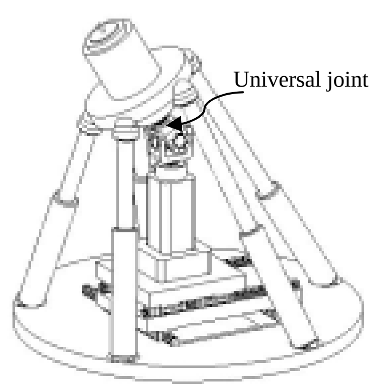


Fig.3: The architecture of the Cartesian guided Pentapod

Static Rigidity

The static rigidity analysis of the CGT includes the compliant elements of the strut, ballscrew, nut, and supporting bearings.. Table 2 lists the analysis results of the telescoping leg CGT at different leg angles (θo). The CGT has a weaker rigidity in the horizontal direction. The horizontal rigidity can be increased by reducing the leg angles (θo), if deteriorating the footprint ratio and transmission ratio by increasing the leg angles (θo) is acceptable. The system rigidity in the horizontal X direction is 67~157N/μm at θo=45°, and 33~83N/μm at θo=60°, for a 50mm ballscrew diameter. Note that there is more than a 250% variation in the stiffness in the working zone.

Table 2 Performance comparisons of CGT

Machine Type	θo	Lo (mm)	S_q (mm)	F_{Rq}	Stiffness			First natural frequency
					Kxx(N/μm)	Kyy(N/μm)	Kzz(N/μm)	
Sliding leg	45°	1,129	846	5.28	146~165	146~165	226~255	98.4 Hz
	60°	949	625	2.81	75~101	75~101	334~371	70.3 Hz
Telescoping leg	45°	936	681	1.73	67~157	70~156	160~239	66.5 Hz
	60°	936	681	1.70	33~83	36~88	271~319	47.7 Hz

Dynamic Stiffness

Because the static system stiffness is different depending on the locations inside the working zone, we were interested in the smallest natural frequency. Tables 6 and 7 show the smallest natural frequency found at different locations for the entire working zone. They are 98.4 Hz and 66.5 Hz for the sliding leg CGT and telescoping leg CGT respectively. The major factors limiting the natural frequency of the CGT are the axial compliance of the ballscrew and the transmission ratio.

Contouring Accuracy

To derive compliant coupled dynamic of the CGT, we assumed that the torsional drive mechanism elements and passive leg guiding mechanisms are rigid systems because they are comparably rigid with the axial drive mechanical elements. By applying the virtual work principle, the compliant dynamic model of the CGT driving system can be formulated as [5]:

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \left(\mathbf{X}_{s,\mathbf{X}}{}^T \mathbf{K}_s \mathbf{X}_{s,\mathbf{X}}\right)\mathbf{X} - \mathbf{F}_g = \left[\boldsymbol{\theta}_{,\mathbf{X}}{}^T \quad \mathbf{X}_{s,\mathbf{X}}{}^T\right] \begin{bmatrix} \boldsymbol{\tau}_m \\ \mathbf{0}_{9\times1} \end{bmatrix}.$$

where, $\mathbf{M}(\mathbf{X}) = \sum_{i=1}^{9}\left(\mathbf{r}_{i,\mathbf{X}}{}^T m_i \mathbf{r}_{i,\mathbf{X}}\right) + \boldsymbol{\theta}_{,\mathbf{X}}{}^T \mathbf{I}_d \boldsymbol{\theta}_{,\mathbf{X}}$, $\mathbf{C}(\mathbf{X},\dot{\mathbf{X}}) = \sum_{i=1}^{9}\left(\mathbf{r}_{i,\mathbf{X}}{}^T m_i \dot{\mathbf{r}}_{i,\mathbf{X}}\right) + \boldsymbol{\theta}_{,\mathbf{X}}{}^T \mathbf{I}_d \dot{\boldsymbol{\theta}}_{,\mathbf{X}}$, $\mathbf{K}_s = diag(k_1, k_2, \cdots, k_9)$ and $\mathbf{F}_g = \sum_{i=1}^{9}\mathbf{r}_{i,\mathbf{X}}{}^T m_i \mathbf{g}$.

In the ***Ks*** matrix, k_1~k_3, k_4~k_6, and k_7~k_9 are stiffness of the ball joint, universal joint and driving system (including axial and torsional) respectively.

The CGT drive control is usually realized in joint space using independent linear P-PI controllers. The P-PI controller means that there is a proportional (k_p) controller in the position control loop and a proportional and integral (k_{vp} and k_{vi}) controller in the velocity loop. To determine the gain values of the P-PI controller, most commercial CNC controller makers suggest that the first natural frequency of the drive mechanism system should be at least 3 times higher than the velocity-loop servo bandwidth. Again, the velocity-loop servo bandwidth should be 3 times higher than the position-loop servo bandwidth.

Figure 4 shows the circular path simulation results when the compliant effect is considered in the servo dynamic model in the high gain case. Compared with the rigid model, significant contouring errors were observed in both the start/stop transient and the steady-state regions although the look-ahead ACC/DEC was applied to smooth the path velocity and acceleration. More than 6 μm and 4 μm compliant-induced errors occurred in the transient and steady-state regions respectively (see Fig. 6-a). Note that the compliant-induced Z error was also found due to the coupled servo dynamics (see Fig. 6-a). Figure 5 shows the elastic deformations in every mechanical component. They were 8 μm, 7 μm and 7 μm for the ballscrew, universal joint and ball joint respectively. These three errors were nearly at the same magnitude because near the home position the ballscrew has stiffness of around 410 N/μm close to the 450 N/μm of the ball- and universal joints. High frequency vibrations with a ±0.2 μm level were found at the start transient region. Through spectrum analysis, these high frequency vibrations corresponded to the resonance mechanical vibration of the platform-leg system.

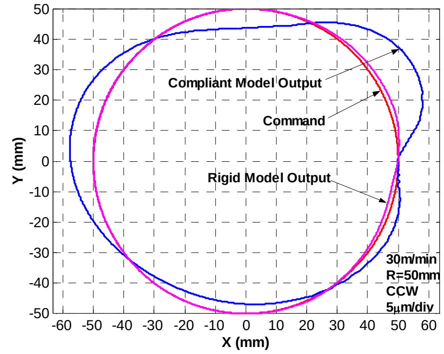


Fig. 4: Comparison of the rigid and compliant models in the high gain case

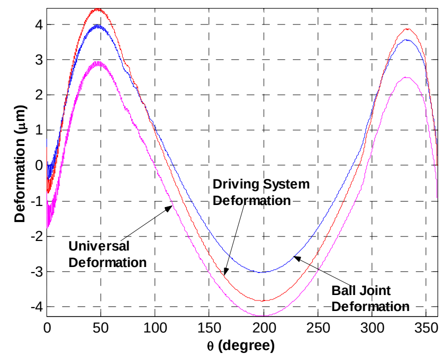


Fig. 5 Compliant components deformations in a circular path

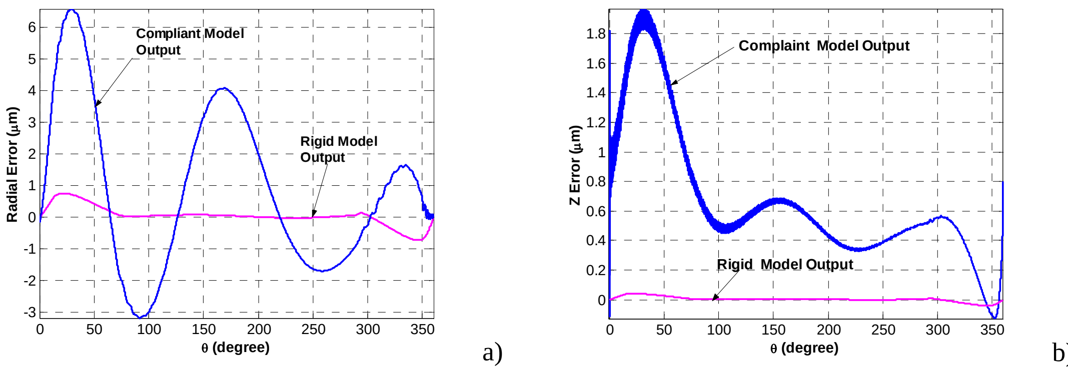


Fig. 6: Compliant-induced contouring error in a high gain case

Conclusions

New parallel mechanism machines called CGT for 3-axis machining, CGP for 5-axis machining, and CGH for 6-axis positioning were presented. The CGT/CGP/CGH has an integrated guiding/metrology leg in that the platform is guided and measured in the Cartesian coordinate system. The CGT/CGP/CGH promises improved accuracy compared with other PKMs using indirect metrology method. Because the CGT/CGP/CGH is controlled and guided in the Cartesian coordinate system, it can be expanded and is compatible with the existing “hard” and “soft” ancillaries designed for conventional Cartesian machine tools and manufacturing processes. The analysis results show that the footprint ratio, static rigidity is comparable to the conventional serial kinematic machine tool. Although the servo dynamic of the CGT is coupled and nonlinear, the conventional linear P-PI control independently implemented at the joint level could produce satisfactory contouring accuracy in a circular motion simulation on a 50mm radius and at a 30m/min feedrate.

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