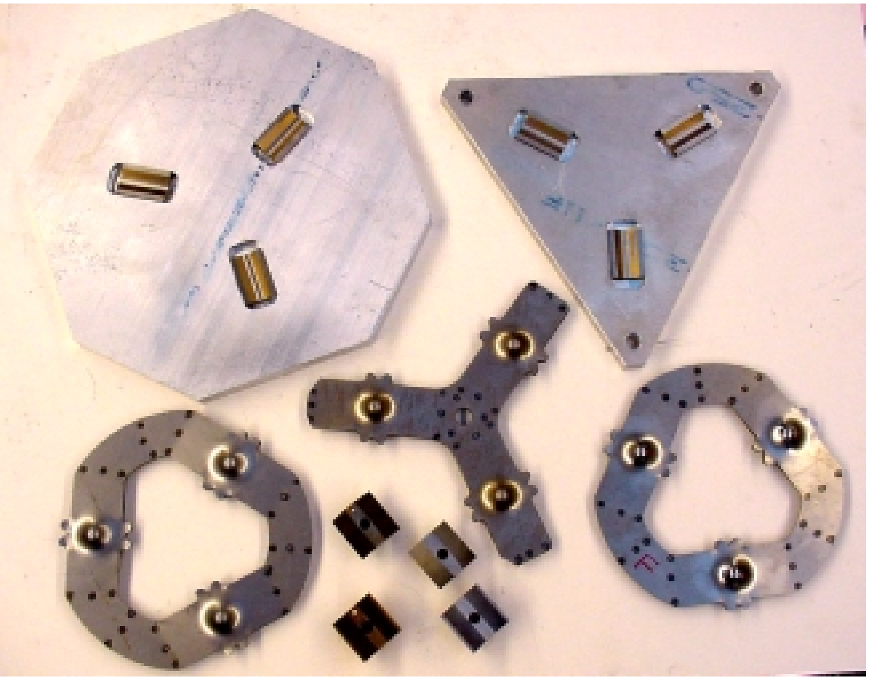
Low Cost Kinematic Couplings

2.75 Fall 2001



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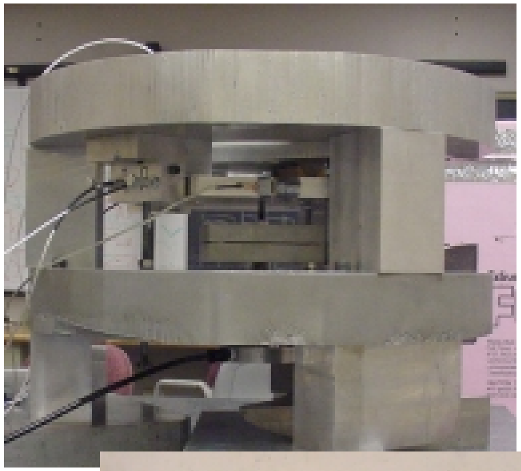
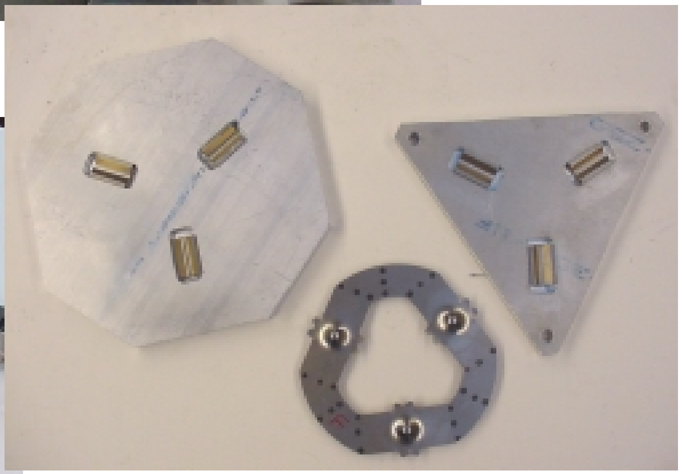
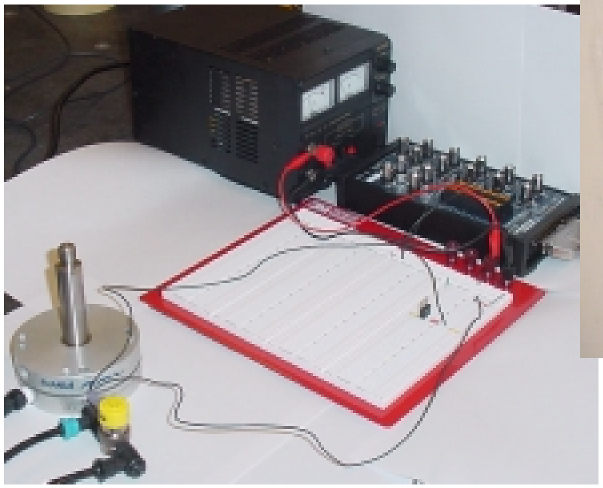
Overview

- Goals/Results
- Spring Washer
- Coatings
- Test Stand
- Test Setup/Testing
- Results
- Future work







Project Goals

- Design and build a low-cost spring washer Kinematic Coupling
- Design and build an automated test apparatus for standardized coupling repeatability measurements
- Experimental investigation on the effect of coatings and lubrication on the repeatability of washer and canoe ball couplings

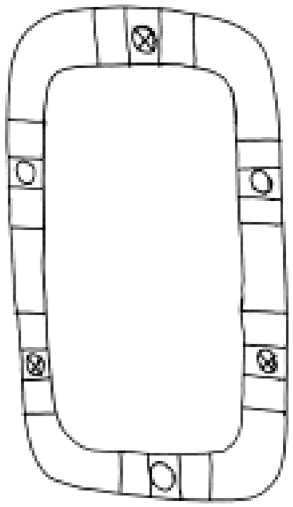
Results Overview

- Radial and tangential spring washers
  - Cost: $200
  - Best repeatability: 133 nm (TiN radial)
- Canoe Balls with different coatings
  - Uncoated: 400 nm
  - TiN: 255 nm
  - TiCN: 54 nm
- Automated test rig
  - Hands free data acquisition

Spring Washer Motivation

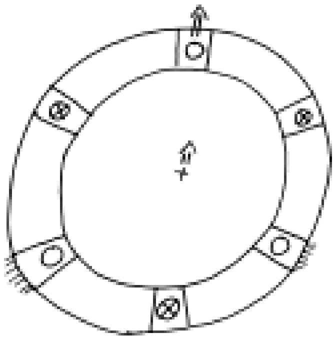
- Many industrial machines, such as ABB robots, could benefit from kinematic interfacing of their components, but require a higher joint stiffness than a standard KC provides.
- Canoe ball couplings are both stiff and repeatable, but come at a high cost (~$1500).
- A kinematic spring washer may have the potential to exhibit high repeatability and stiffness at a much lower cost (~$200).

Spring Washer Evolution



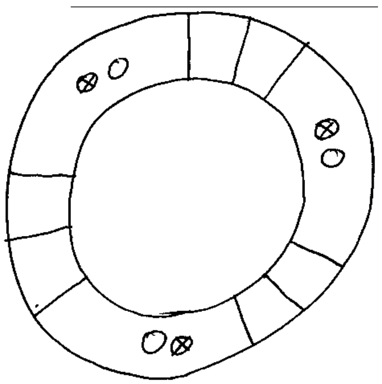
Original Idea, directly from Slocum et al patent

- X denotes deformation into the plane, blank out of the plane



First Brainstorming Iteration

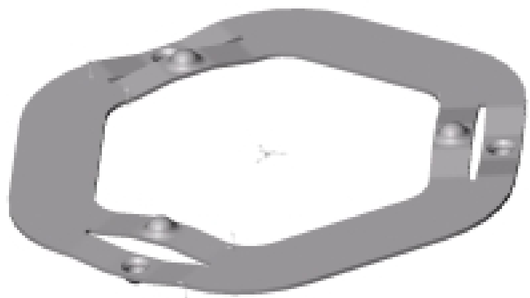
- Reduced the number of folds
- Added radial symmetry



Second Iteration

- Brought the features that need to be located relative to one another closer together
- Eliminated compliance

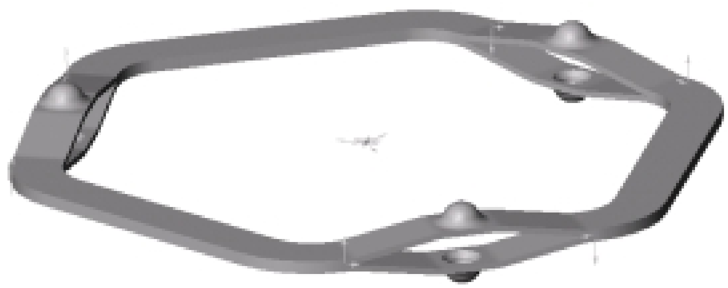
Spring Washer Evolution



Third Iteration

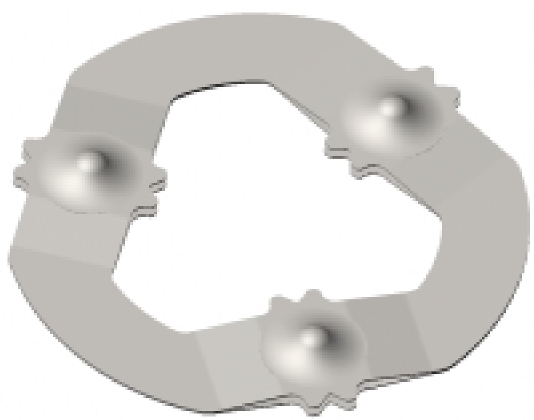
• Arranged bumps radially and added a slot feature to restore compliance

• If the center of the sphere falls on the instant center of the four-bar "linkage", sideways motion is non-critical



Fourth Iteration – back to back design

- Unidirectional forming, fewer and more widely spaced features
- NO critical tolerances in the stamping process – welding determines X, Y, θ_z of the mated part.
- Welding also counteracts warping



Final Design

- Wider for desired stiffness and stress characteristics
- Larger relief radius required for forming
- Tabs for feature location during manufacturing

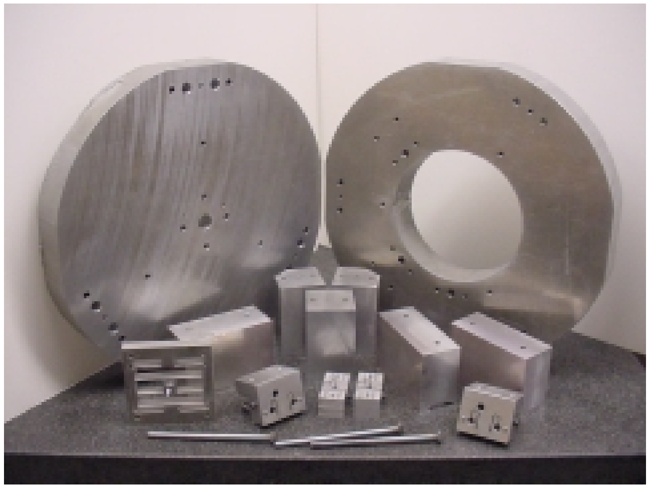
Coatings

Coating	TiN	TiN + WS_2	TiCN	TiAlN	CrN	ZrN
Hardness HK[1]	2200	2200	2800	3500	2200	3300
Coefficient of Friction	0.50	~0.03	0.40	0.60	0.50	0.50
Adhesion[2] [N]	>55	>55	>50	>50	>70	>45
Relative Cost [$]	1	1.7	1.4	1.4	1.4	1.4
Lead Time [Weeks]	2	2	2	4	4	4

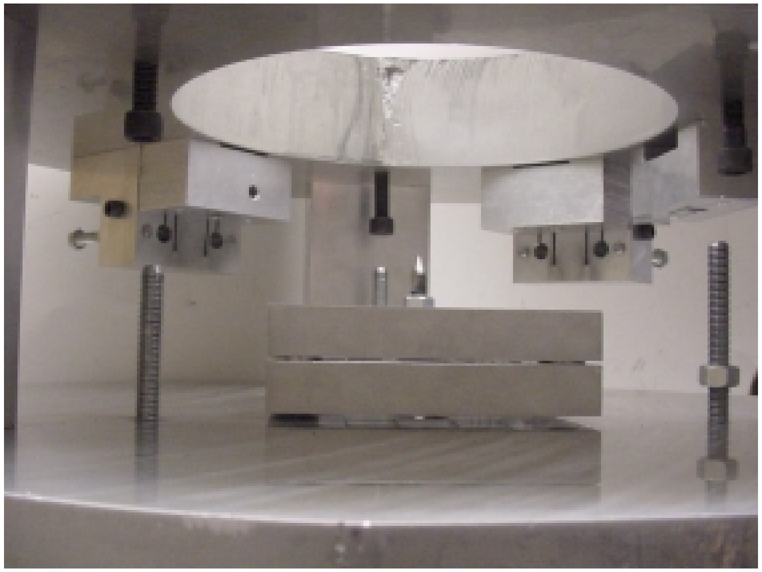
Motivation:

- Coatings increase the energy required to alter the surface: wear, fret, corrode, plastically deform. They also decrease friction. Both factors should improve repeatability.
- Titanium Nitride and Titanium Carbonitride were the coatings of choice. *Both* were additionally treated with Tungsten Disulfide to reduce friction.
- Brycoat Corporation in Florida has generously donated their coating services to the lab. If you are interested in having parts coated, talk to Ken or Willie at (727) 726-3500. We were very pleased with their work.

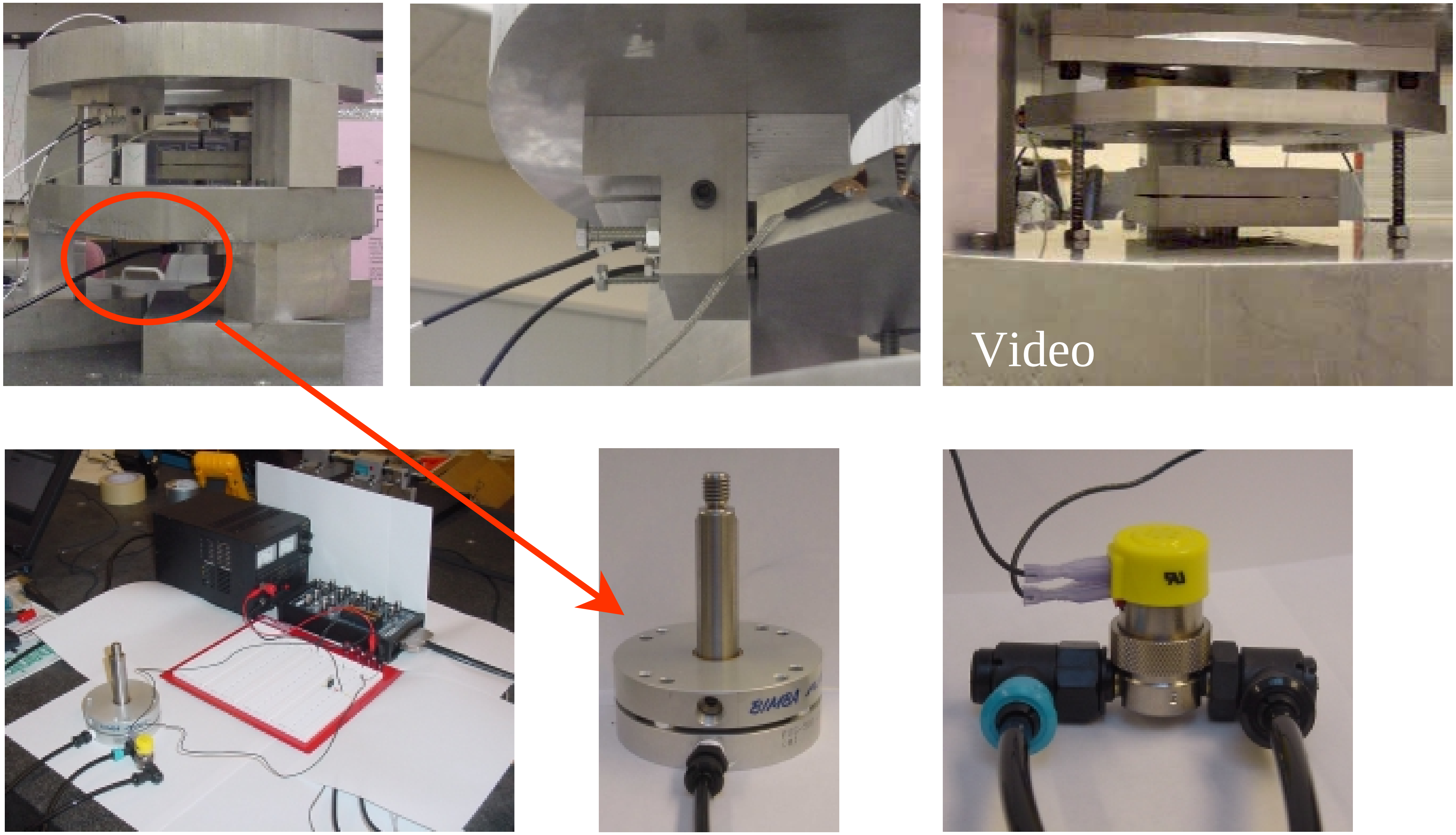
Automated Testing



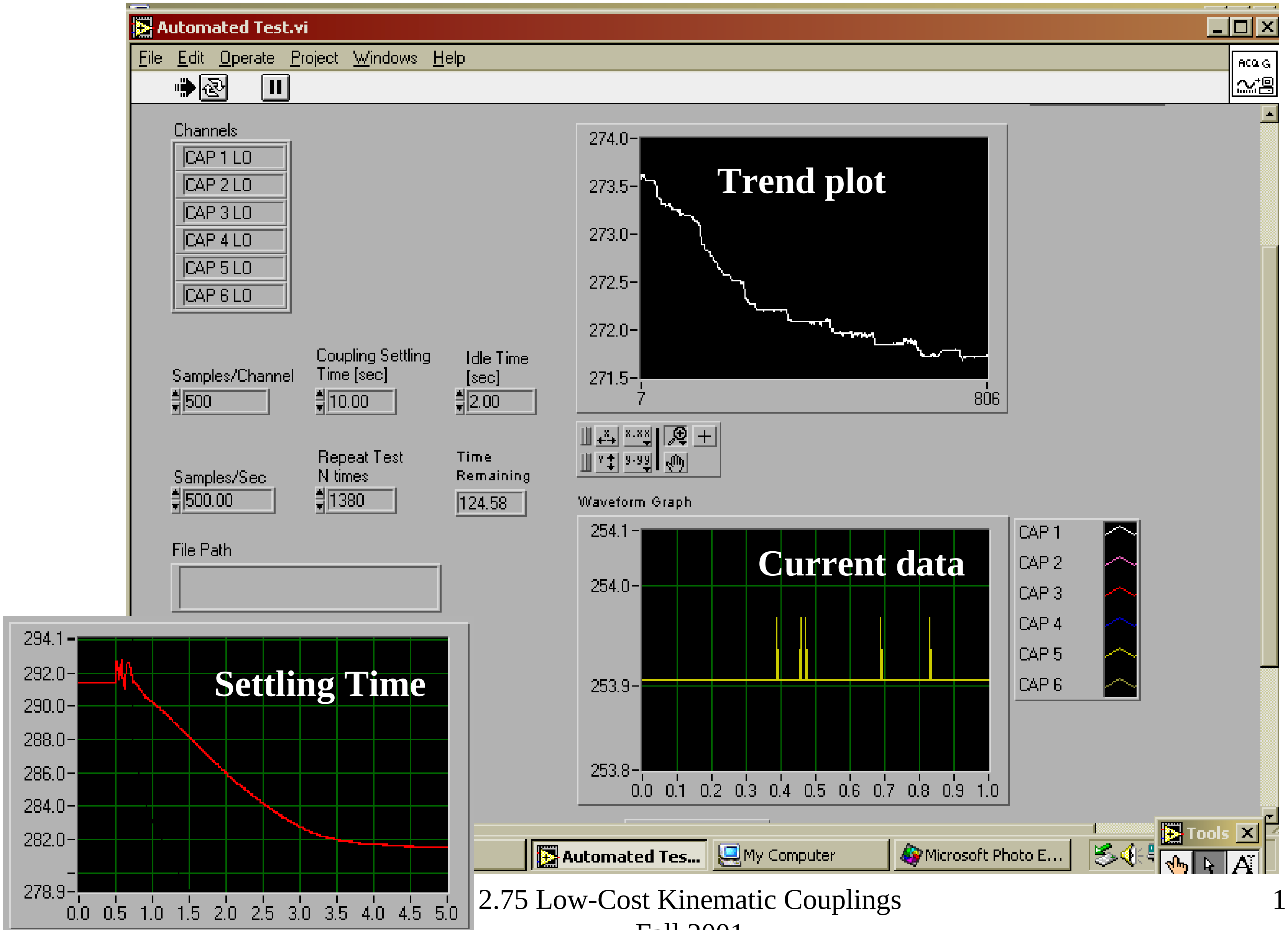
- 12 unique parts / 24 total
- Measures all 6 DOF of bottom coupling plate
- Pneumatic force application
- Flexures minimize wobble pin tangential forces
- Radial symmetry for thermal robustness
- Hard stops protect in-plane probes



Test Setup



Test Runs


Automated Test.vi
File Edit Operate Project Windows Help
Channels
CAP 1 LO
CAP 2 LO
CAP 3 LO
CAP 4 LO
CAP 5 LO
CAP 6 LO
Samples/Channel
500
Coupling Settling Time [sec]
10.00
Idle Time [sec]
2.00
Samples/Sec
500.00
Repeat Test N times
1380
Time Remaining
124.58
File Path
Trend plot
Waveform Graph
Current data
CAP 1
CAP 2
CAP 3
CAP 4
CAP 5
CAP 6
Settling Time
Automated Tes...
My Computer
Microsoft Photo E...
Tools

Detailed Repeatability Results

	Cap filtered	Cap actual	Linear f'd	Angular f'd
	nanometers	nanometers	nanometers	microrads
30 Minute Probe Drift	**23**	62	14	0.4
Canoe Balls Plain	**400**	11,960	332	3.7
Canoe Balls TiN	**255**	669	179	0.3
Canoe Balls TiCN	**54**	316	34	1.0
Ring Washer Plain	**6,469**	33,030	8,284	75.1
Ring Washer TiN	**226**	3,492	232	6.9
Radial Washer TiN	**133**	156	182	3.9

- All values are incremental repeatability = current minus previous value.

-This chart represents several million measurements.

-"Actual" repeatability is (max – min) / 2. "Filtered" repeatability eliminates obvious outliers (compressor!).

- Noise was measured before grounding error was corrected, but is still acceptable.

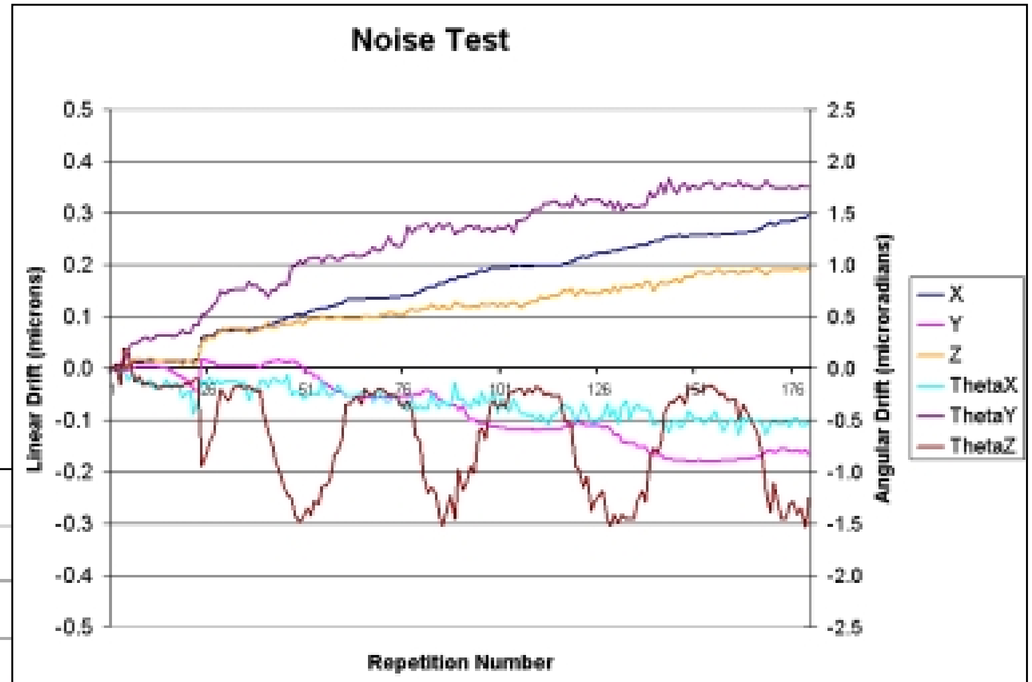
- Plain washers required manual settling, since friction is above the critical value for seating.

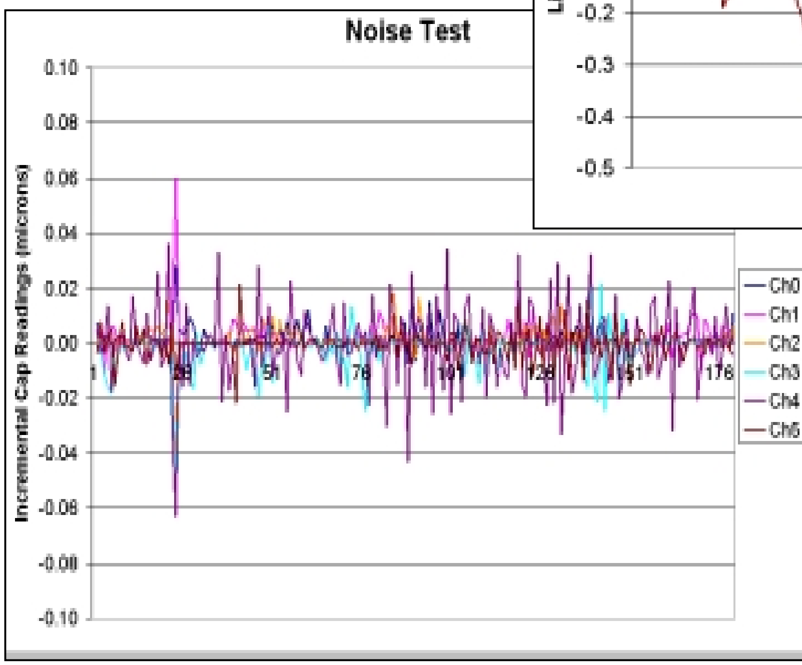
- Only in-plane measurements were taken for the washers.

Noise Test

Canoe ball coupling was left engaged for 30 minutes

Wiring mistakes probably contributed to drift

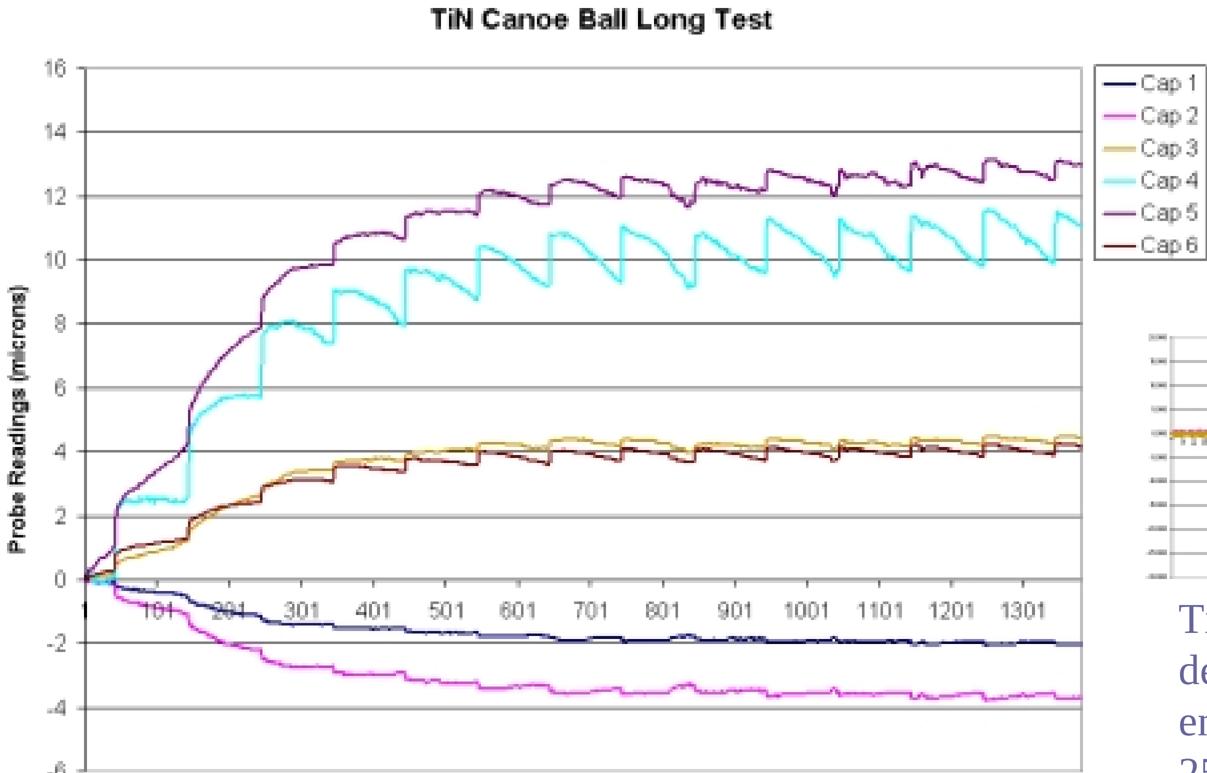


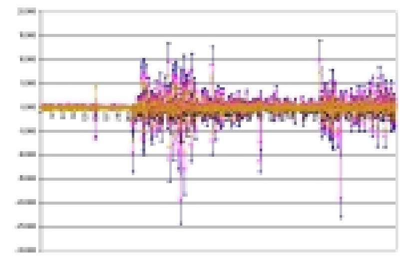


Noise is below 20 nm for 95% of tests

Net drift is less than 0.4 microns in position

TiN Canoe Endurance Test





TiN ring washer degenerates after endurance test after 250 cycles (plus previous 100)

- Clear evidence for air compressor / pressure imperfection

- Coupling gets better with time – lubricant layer is reduced and brinelling of surfaces occurs.

- Some tests are unbelievably close to the previous one – 18 tests in a row, probe 3 drift was less than 2 Angstroms (1199-1217)!

Spring Washer Cost Breakdown

Total Production Cost Per Washer: $200

- Stamping and material cost: $1.30
  - Tooling cost per washer: $0.50
- TiN coating: $106; TiCN coating: $147
- WS_2 coating: $78
- Other costs: welding, polishing, packaging
- Coatings drive most of the cost
- BryCoat is not equipped to do large production runs. They have to place washers vertically

Results Summary

Repeatability (nm)	Plain	TiN	TiCN
Ring Washer	6,500	226	N/A
Radial Washer	N/A	133	N/A
Washer Cost	$2	$186	$227
Canoe Ball	400	255	54

- Plain spring washers do not work.
- TiN is good, TiCN is surprisingly better – friction coefficient of 0.4 vs. 0.5, but critical value may be 0.55
- In our tests, coated washers beat coated canoe balls!

Future Work

- The spring washer concept looks promising, but needs further development before it can be applied.
  - Can lubricants economically provide similar effects as coatings?
  - How can the interface be rigidly joined without degradation of repeatability?
  - How do washers behave without lubricant?
  - Can geometry (contact radius, etc) be optimized?
  - Effect of manufacturing tolerances on performance of coupling?
- Recommendations
  - Standardize coupling triangle contact diameter
  - Invest in a better pressure regulation valve
  - Measure friction coefficients
  - Test polished canoe balls that do not have machining “lines” to see if 0.03 friction can be approached

Questions?