

Kinematic Couplings and Elastic Averaging

Precision, Intelligent, Low Cost Interfaces with Medical Applications?

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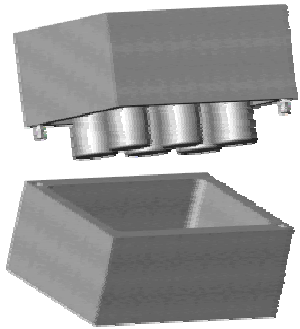


Introduction

- Kinematic Coupling Basics
- Projects and Examples
- Exchangeability and Data Handling
- Potential Medical Applications?
- Demonstration



Overview of Common Coupling Methods



Pinned Joints

No Unique Position



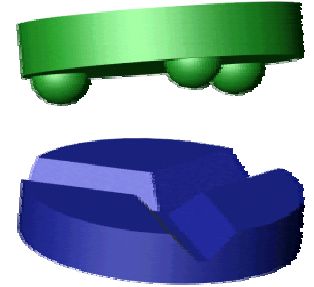
Flexural Kin. Couplings

Kinematic Constraint



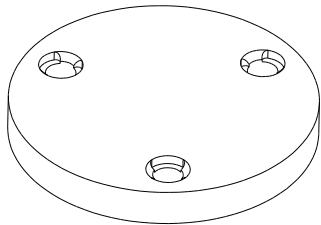
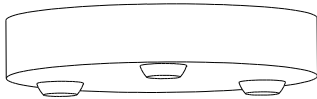
Elastic Averaging

Non-Deterministic



Kinematic Couplings

Kinematic Constraint



Quasi-Kinematic Couplings

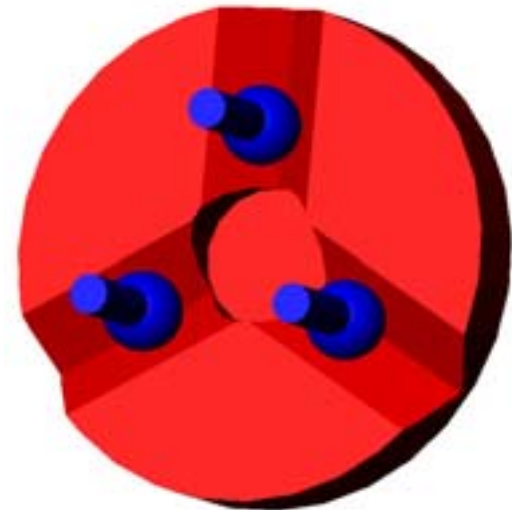
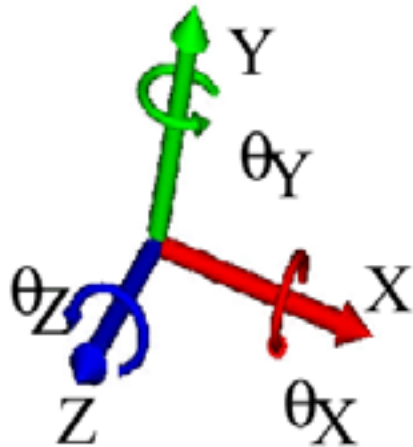
Near Kinematic Constraint

	0.01 μm	0.10 μm	1.0 μm	10 μm	100 μm
Pinned Joints				[Blue bar]	
Flexural Kinematic Couplings				[Blue bar]	
Elastic Averaging				[Blue bar]	
Quasi-Kinematic Couplings				[Blue bar]	
Kinematic Couplings				[Blue bar]	



Exact Constraint (Kinematic) Design

- Exact constraint means a component has an equal number of constrained points to number of degrees of freedom
- If component is over constrained, clearance and high tolerances required to prevent premature failure or assembly incompatibility
- Kinematic design means that the motion is exactly constrained and geometric equations can be written to describe its motion
- Kinematic Couplings constrain components exactly, commonly providing repeatability of $\frac{1}{4}$ micron or on the order of parts' surface finish
- Managing Hertz contact stresses is the key to successful kinematic coupling design

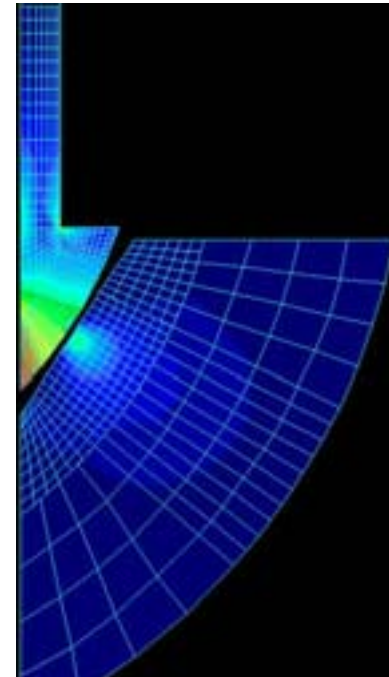
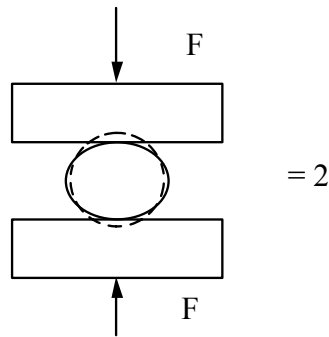


Hertz Contact Stress

- Heinrich Hertz, the mathematician famous for his work in the frequency domain, also created the first analytical solution for determining the stress between two bodies in point contact
- Exact constraint design often creates contact at single points, creating high stresses
- Creative solutions, such as canoe balls and quasi-kinematic couplings, help alleviate contact problems

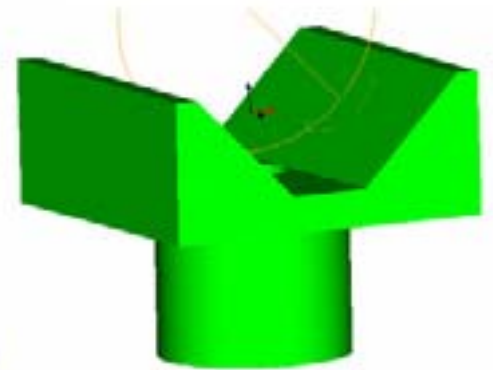


Heinrich Hertz 1857-1894



Load Capacity of Kinematic Elements

- The “Canoe Ball” shape is the secret to the design
- It acts like a ball 1 meter in diameter
- It has 100 times the stiffness and load capacity of a *normal* 1” ball
- It has 10 times the load capacity of a crowned-cone
- The large shallow Hertzian zone is *very* repeatable



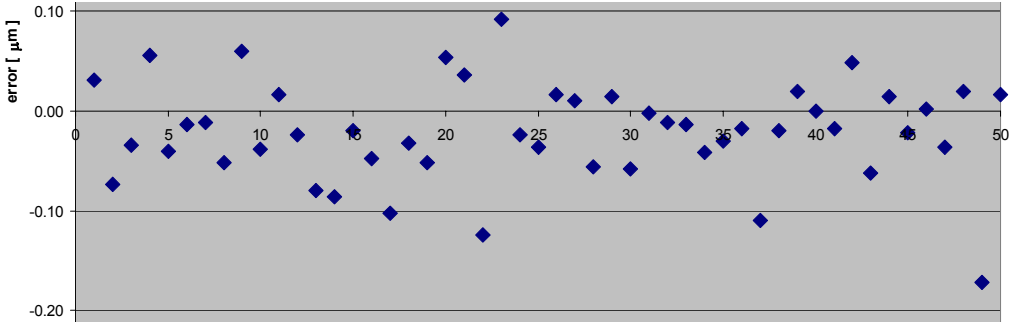
US Patent 5,711,647



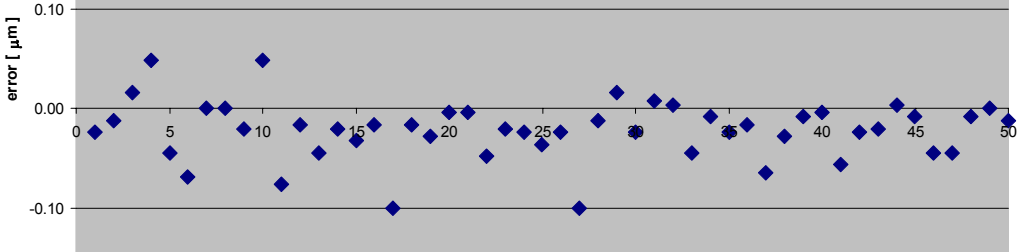
Canoe Ball Repeatability Measurements



Coupling



Measurement system

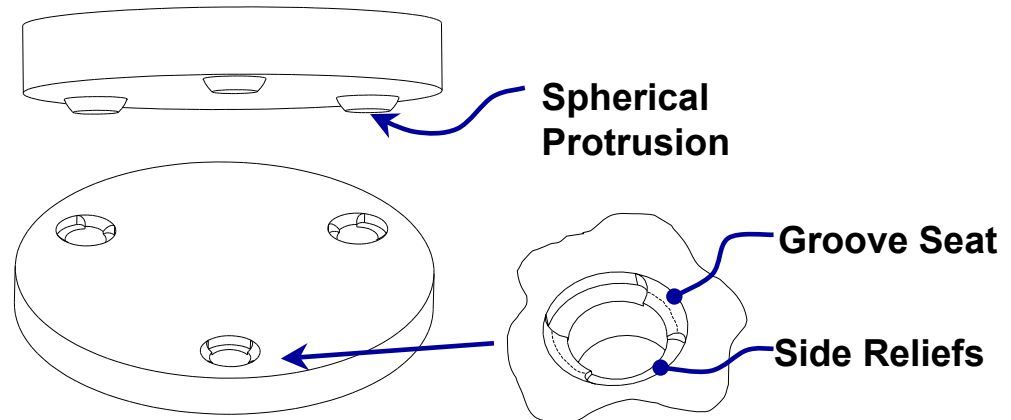


Quasi-Kinematic Couplings (QKC's)



QKC Attributes and Characteristics:

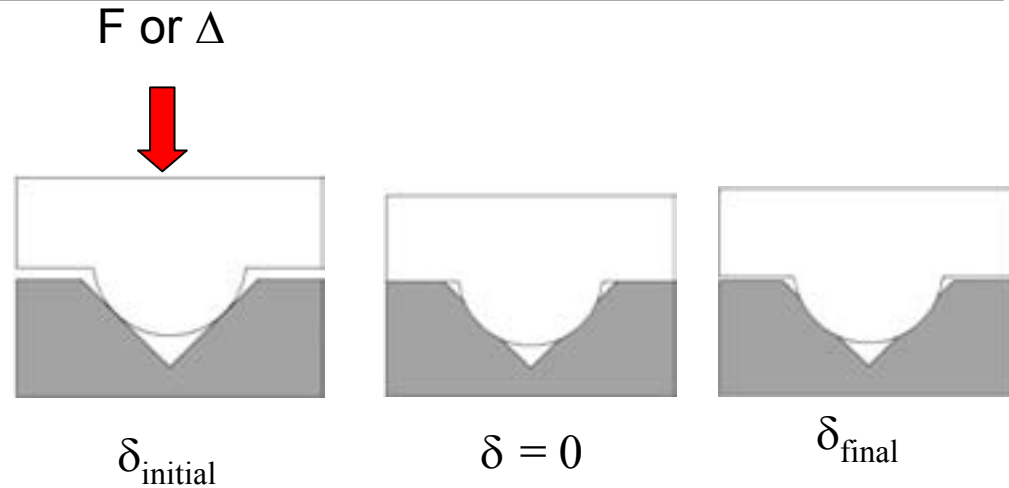
- Surfaces of Revolution -> Line Contact
- Weakly Over-constrained
- Sub-micron Repeatability
- Sealing Contact
- High Stiffness



QKC Function

PROCESS:

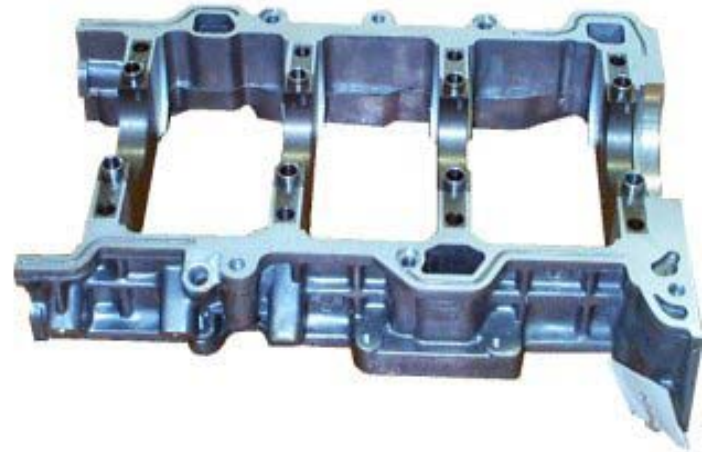
- Mating force/displacement applied
- Ball & groove comply
- Brinell out surface finish
- Elastic recovery restores gap



Application: Location of Engine Components



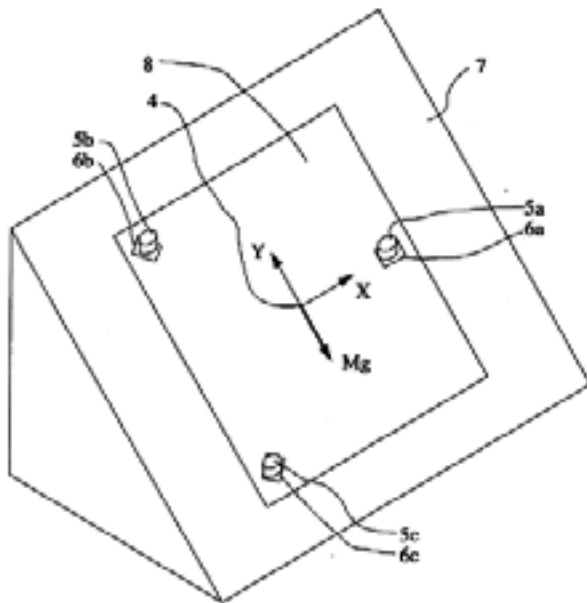
Block



Bedplate



There are *MANY* other uses for Kinematic Couplings....



- The Kinematic Sheet Coupling was created for the Printed Circuit Board (PCB) industry
- It provides 10x greater repeatability than traditional 4 pins-in-4-slots method



Example: Three-Tooth Couplings

- A semi-kinematic effect can be achieved by having three teeth each on two coupling halves mate at six points
 - 3-5 micron repeatability can be obtained with this simple design
- Layton Hale at LLNL put crowns on one set of the teeth to create a nearly true kinematic three tooth coupling:
 - 1 micron repeatability can be obtained with this simple design



United States Patent (17) Hale

[54] THREE-TOOTH KINEMATIC COUPLING

[75] Inventor: Layton C. Hale, Livermore, Calif.

[73] Assignee: The Regents of the University of California, Oakland, Calif.

[*] Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 5.54 days.

[21] Appl. No. 08511300

[22] Filed: Aug. 7, 1998

[51] Int. Cl. 7: F16D 1/00

[52] U.S. Cl.: 403/364; 403/373; 403/369; 403/371; 403/372; 403/373

[58] Field of Search: 403/364, 369, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000

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[11] Patent Number: 6,065,898

[12] Date of Patent: *May 23, 2000

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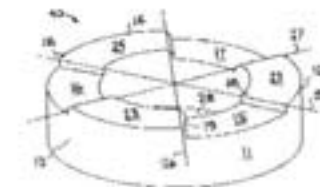
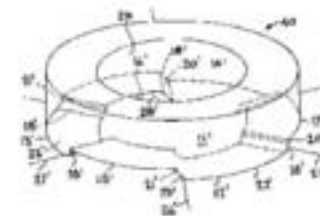
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Primary Examiner: David P. Swales
Assistant Examiner: Brian A. Lee
Attorney Agent: or: Peter Allen H. Thompson, T. B. O'Connell

[17] ABSTRACT

A three-tooth kinematic coupling based on having three thousandths of an inch contact formed by mating teeth rather than six thousandths per inch. The geometry requires one coupling half to have rounded teeth and the other coupling half to have the teeth. Each coupling half has a rounded outer profile which does not affect the kinematics, but in the limit of the face width approaches flat. Thus, line contacts become six point contacts. As a result of having line contact, a three-tooth coupling has greater load capacity and stiffness. The kinematic coupling has application for use in precision fixtures for tools or workpieces, and as a manufacturing device for a work or tool changer or for optics in various products.

13 Claims, 2 Drawing Sheets



Example: Magnet Preloading for Indicator Arm

- Preload MUST be repeatable
- Preload must be high and thus must NOT deform the rest of the structure
 - Preload through the center of the kinematic elements with bolts
 - Preload an instrument coupling with magnets
 - Example: Kinematic coupling used to hold probe arm to an electronic indicator (US patent 4,574,625, assigned to Federal Products Corp.).

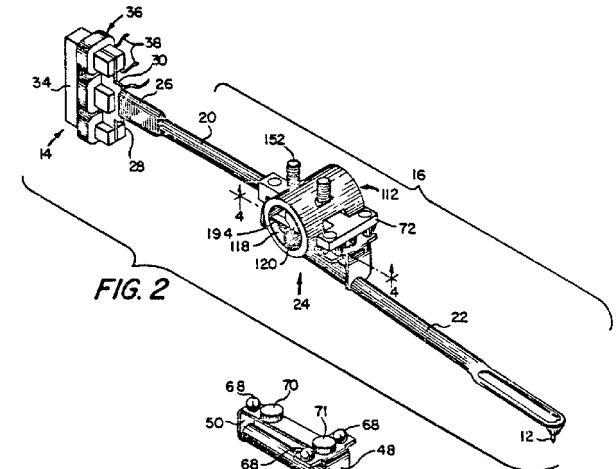
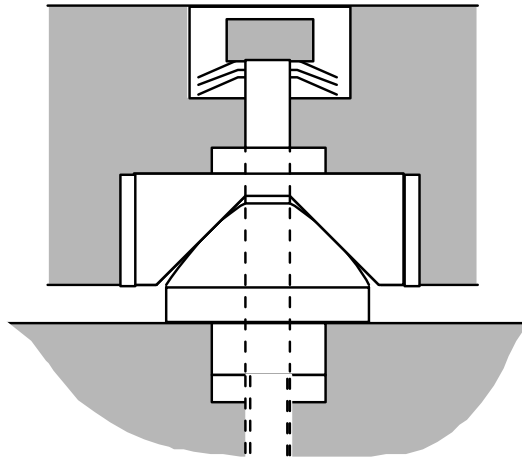


FIG. 2

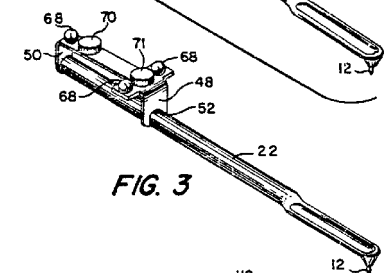


FIG. 3

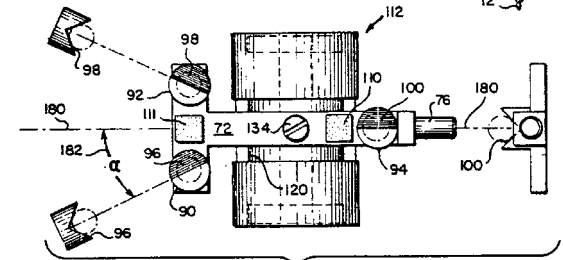


FIG. 4



Current Projects for ABB IRB6400

Use kinematic couplings to enable quick-change modularity of industrial robots:

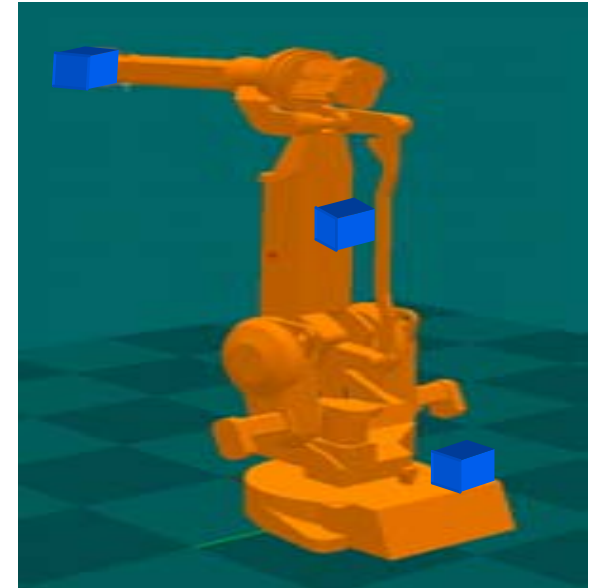
- **Measurement interface** - repeatable attachment of a quick-calibration inclinometer device to the robot structure, small size and loading
- **Structural interface** - repeatable and exchangeable attachment of the manipulator wrist to the remainder of the structure, medium size and loading
- **Factory interface** - repeatable and exchangeable attachment of the manipulator to the factory floor, large size and extensive dynamic loading

Require NO online calibration after module replacement



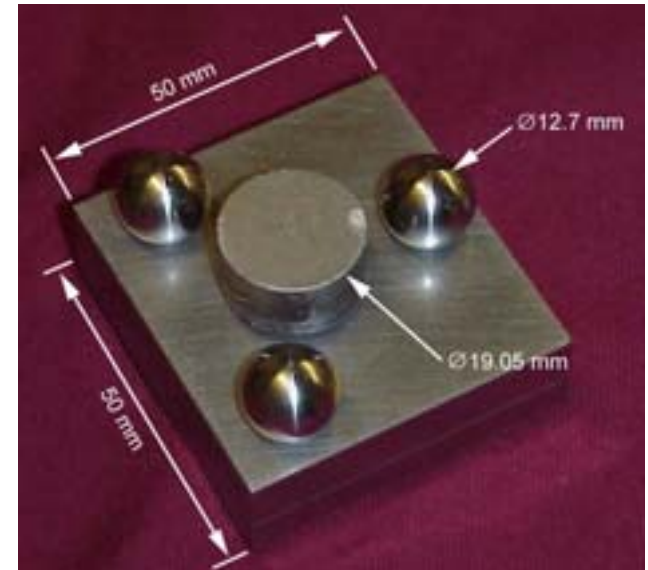
Measurement Interface: The Wonder Wyler

- Device to calibrate angles of the six robot axes
- Consists of two inclinometers at right angles
- Measurements at six locations on robot
- Adjusts robot to desired zero angles and recalibrates controller to these values



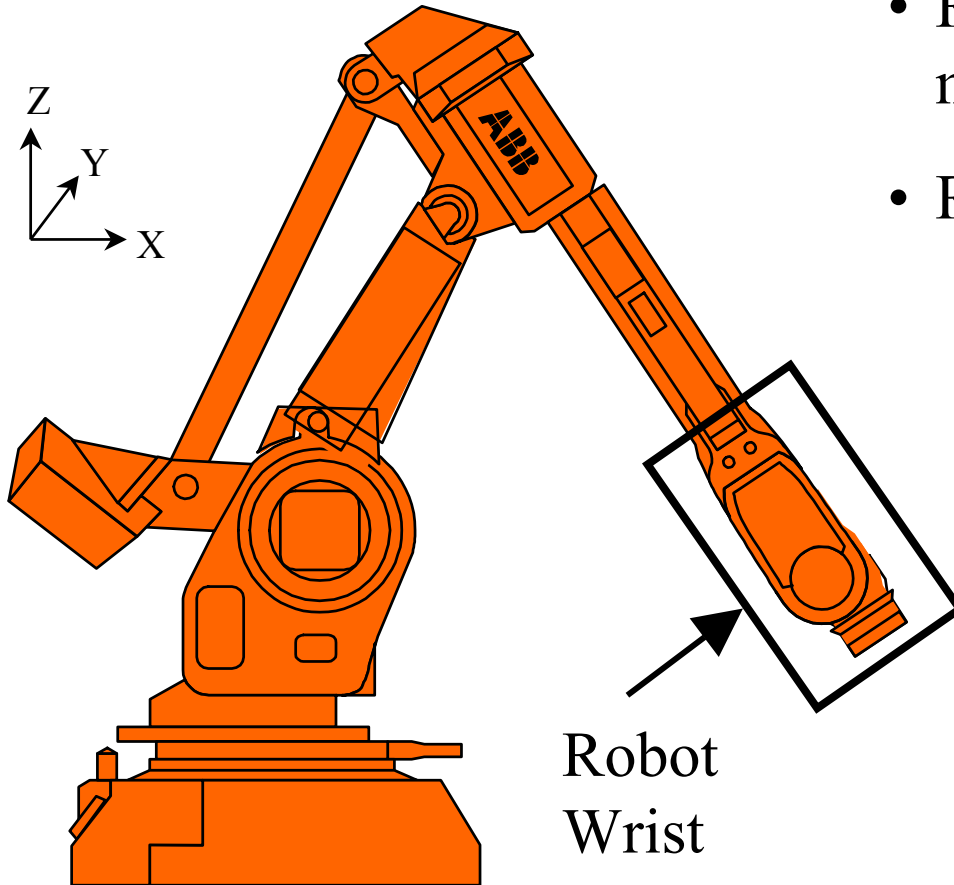
Design Goals

- Portable and compact device
- Secured coupling for both vertical and horizontal mounting using magnets
- Accurate and repeatable coupling to ± 0.01 degrees
- Adaptable to various robot sizes
- Patent application for calibration method and device



Structural Interface: Robot Wrist Replacement

- Replacement time - 30 to 60 minutes plus recalibration
- Repeatability to $\sim 1\text{mm}$

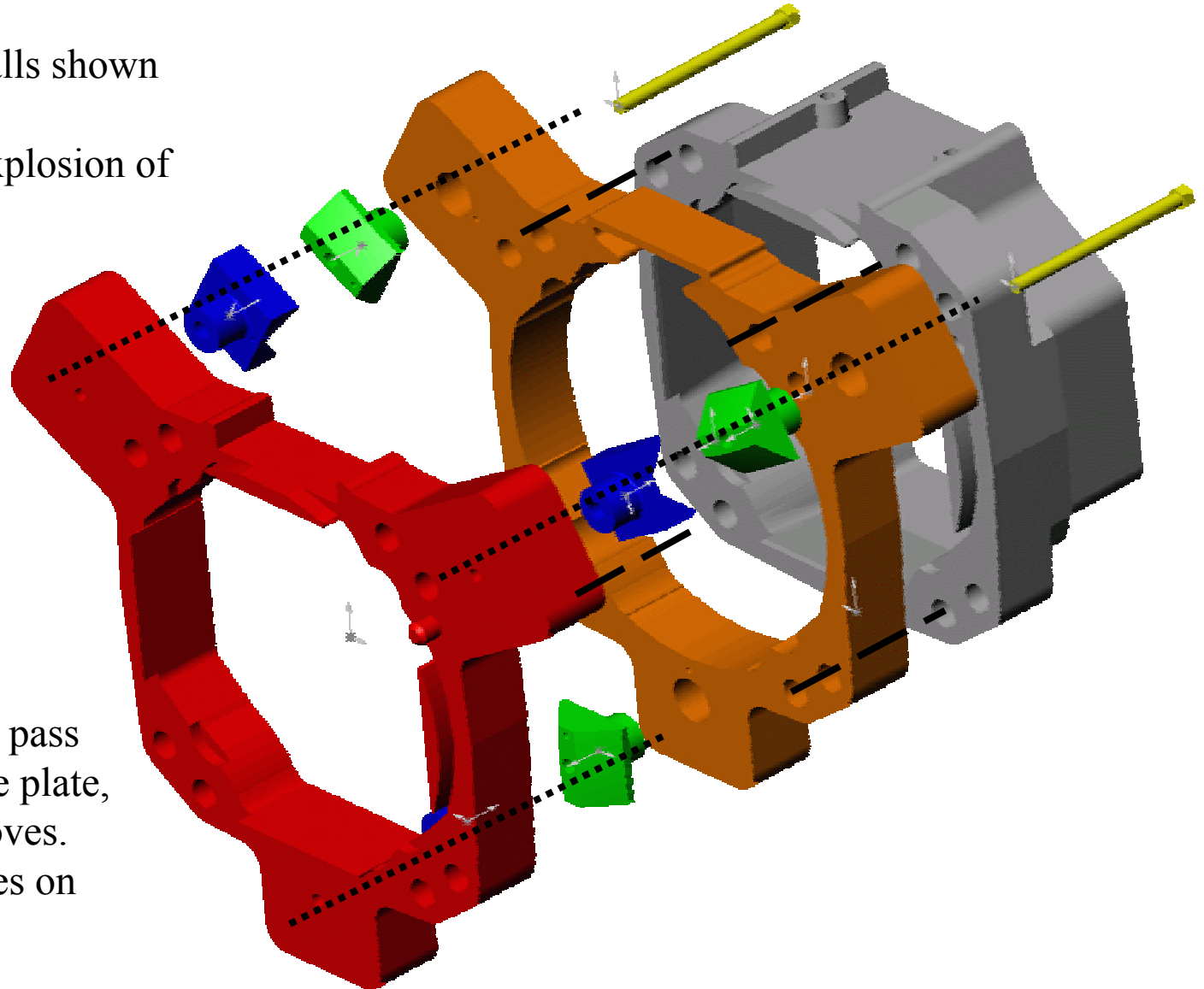


Note: Robot is in Wrist Removal Position



Initial Design for Canoe Balls and Grooves on Wrist

Design uses canoe balls shown earlier
Short dashes show explosion of grooves and balls



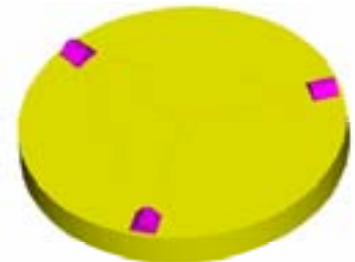
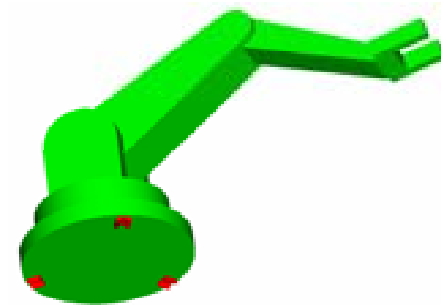
Yellow preload bolts pass through arm interface plate, canoe balls, and grooves. Bolts thread into holes on wrist plate.



Factory Interface: Robot Manipulator Mount

Use kinematic locators between robot foot and floor-mounted baseplate, redefining the installation and replacement processes:

- Calibrate production robots to a master baseplate at the robot factory
- Install individual baseplates at the line site and calibrate directly to tooling
- Measure couplings directly and predict interface error as a frame transformation
- Reduces replacement error at tool (TCP) from 0.8 mm to 0.10 mm – no path touch-up required



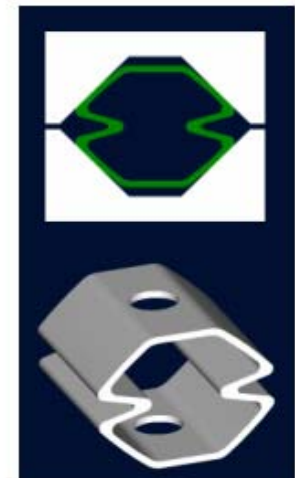
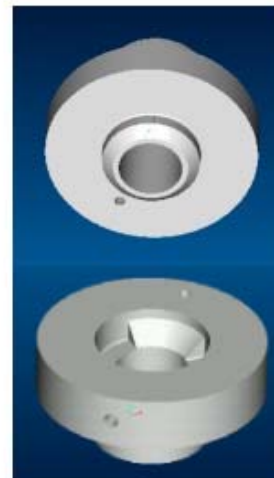
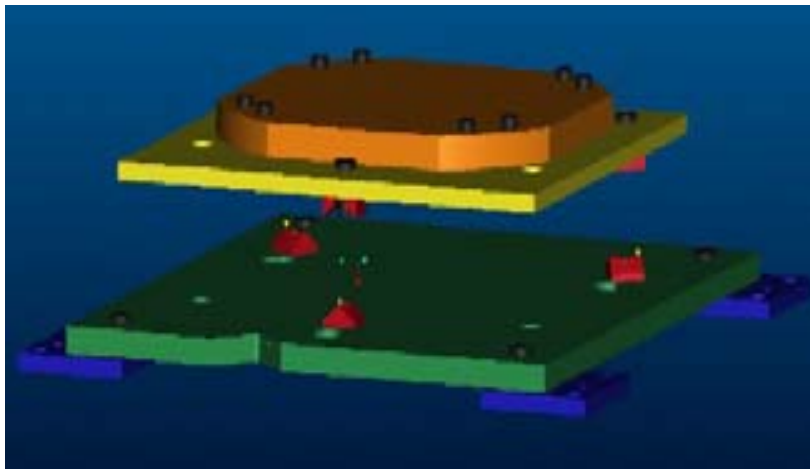
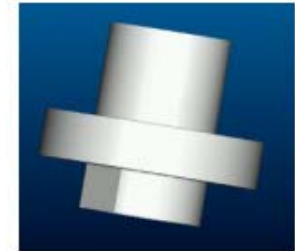
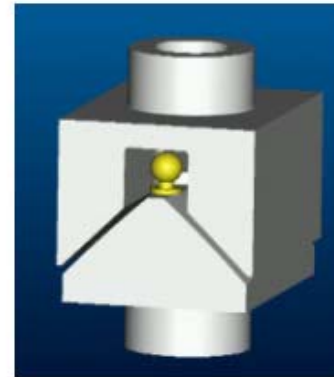
Benefits \$10,000 per minute of downtime saved



Factory Interface Coupling Concepts

Compare long-term static and dynamic performance of kinematic interfaces for the base:

- (1) Canoe ball couplings
- (2) Three-pin coupling
- (3) Standard quasi-kinematic couplings
- (4) Low-cost extruded quasi-kinematic couplings



Calibration for Exchangeability

Modular components demand blind, accurate exchangeability – supplants traditional adequacy of high repeatability

Solution: Kinematic coupling with integrated measurement feature

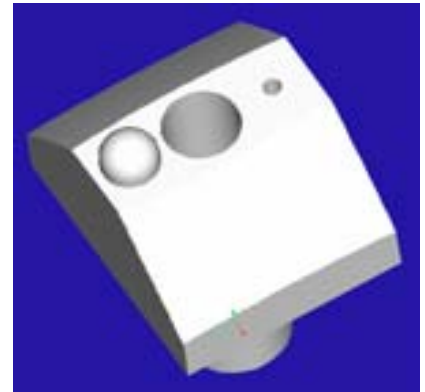
- Measure hemispherical features on each ball and groove
- Short measurement loop between feature and kinematic contact points minimizes variational error
- Calibration software finds deterministic error transformation between interface frames

$$T_{Robot} = T_{Base-1} T_{1-2} T_{2-3} T_{3-4} T_{4-5} T_{5-6} T_{6-TCP} \quad T_{Robot} = T_{Base-1} T_{1-2} T_{2-3} T_{3-4} T_{4-5} T_{5-6} T_{6-TCP}$$

$$T_{cell, nom} = T_{Base-User} \quad T_{cell} = T_{interface} T_{Base-User}$$

$$T_{error} = T_{cell} T_{robot}^{-1} \quad T_{error} = T_{robot}^{-1} (T_{interface} T_{cell, nom})$$

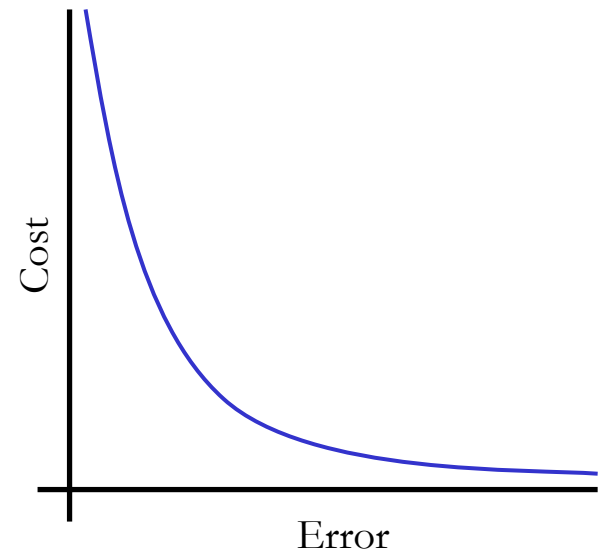
$$\arg(T_{error}) \ll \arg(T_{error, nom})$$



Standard Representation

Standardize kinematic interfaces for wide-scale implementation

- Deterministic behavior = discrete parameter representation
 - Repeatability = $f(\text{material}, \text{type})$
 - Exchangeability = $f(\text{manufacturing tolerances}, \text{type})$
 - Load capacity = $f(\text{geometry}, \text{material})$
 - Long-term performance = $f(\text{material}, \text{type}, \text{load condition})$
 - (etc)....
- Standardized interface is **easy to encode** for calibration and efficient parameter transmission
- Offer a cost vs. accuracy “menu” to customers – pick standard interface suited to application = **desired accuracy at minimum cost**



Intelligent Data Handling

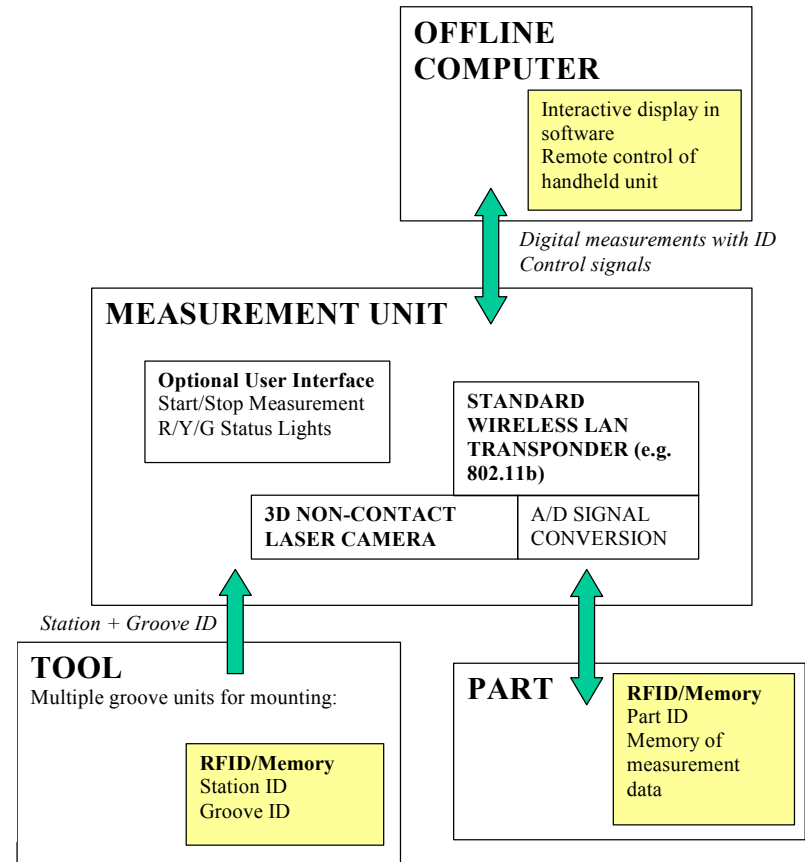
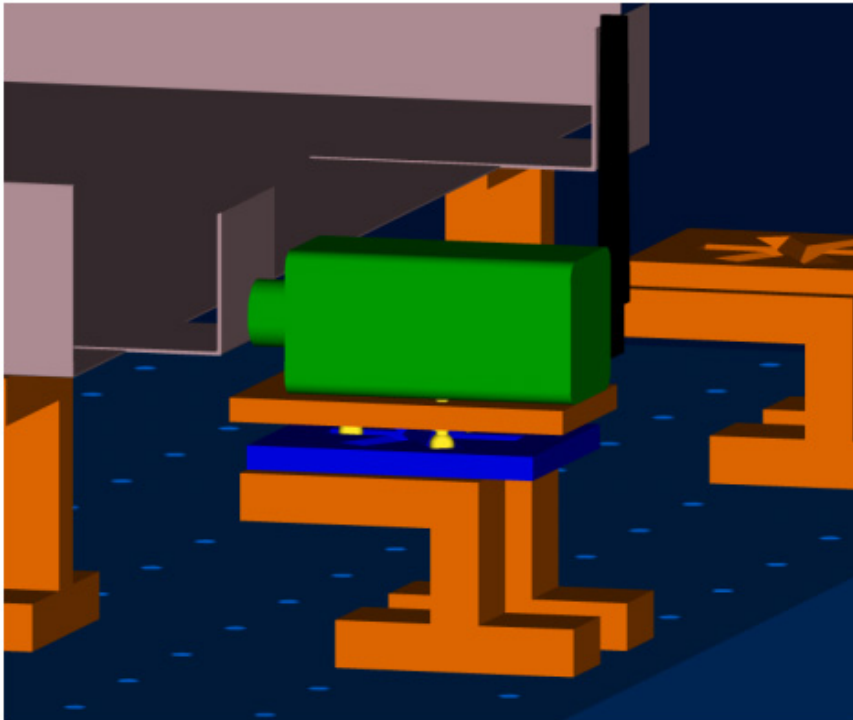
Couple kinematic interfaces with short-range wireless communications technologies to build intelligent systems

- Replace calibration diskettes with RFID chips, and proximity detection initiates :
 - Auto-identification of installed module (ID, type, and location)
 - Auto-calculation of error transformations when a model is replaced
- Encode measurement data on parts in process
- Correct for major variation with active kinematic fixtures
- Transponders in machines act as peer-to-peer repeaters, extending the wireless network factory-wide with minimal cabling



Wireless Concept: Measurement Tool

Wireless tool for instant dimensional troubleshooting in automotive assembly stations:

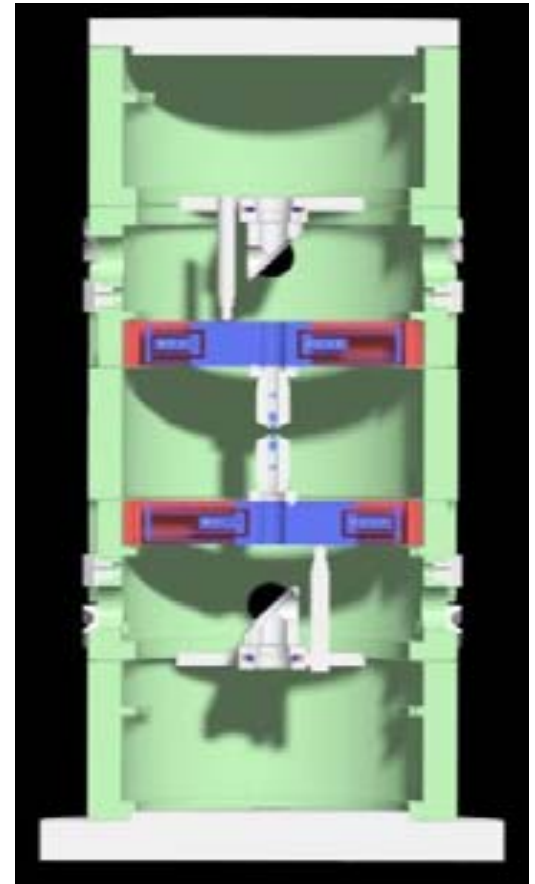


Application: Modular Microscope

Working with U. Illinois Laboratory for Fluorescence Dynamics (LFD) on development of modular biological instrumentation:

Traditional microscopes are inadequate for single-molecule experiments (e.g. force measurements during DNA protein binding), which demand:

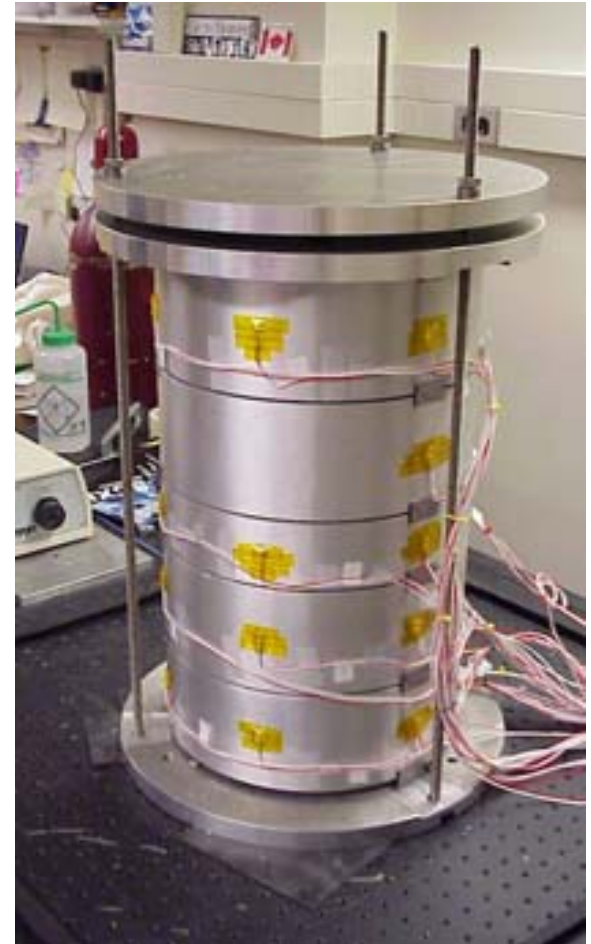
- Nanometer-scale optical resolution
- Flexibility to accept widely different optical modules and instrumentation peripherals
- Ability to reconfigure the optical setup without re-calibration
- Structural resistance to vibration and acoustic noise
- Stability of the optical environment within nanometers over hour-long experiments



Modular Kinematic Solution

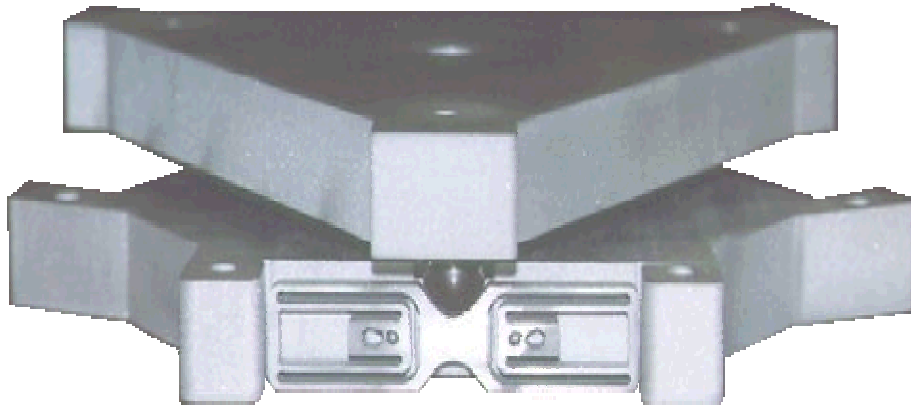
Modularize the structure using kinematic canoe locators:

- Stable under thermal disturbances:
 - Rings direct heat to angular uniformity
 - Couplings act as thermal isolators
 - Design permits uniform axial and radial expansion
- 0.1 micron repeatability of kinematic couplings makes re-alignment automatic
- Optics can be attached to pre-calibrated replacement modules, simplifying experimental setup
- Smaller rings are less expensive to fabricate than a single, high-precision column



Example: Compliant Kinematic Couplings

- How can high repeatability be obtained without tipping instability?
 - Decouple the FRS
 - 1st achieve kinematic coupling
 - 2nd clamp surfaces together while allowing the kinematic elements to translate



Components to Design in CKCs:

- Clamping Load / Friction / Mated Surface
- Joint Location
- Compliant Members
- Kinematic Interface



Not Flexed



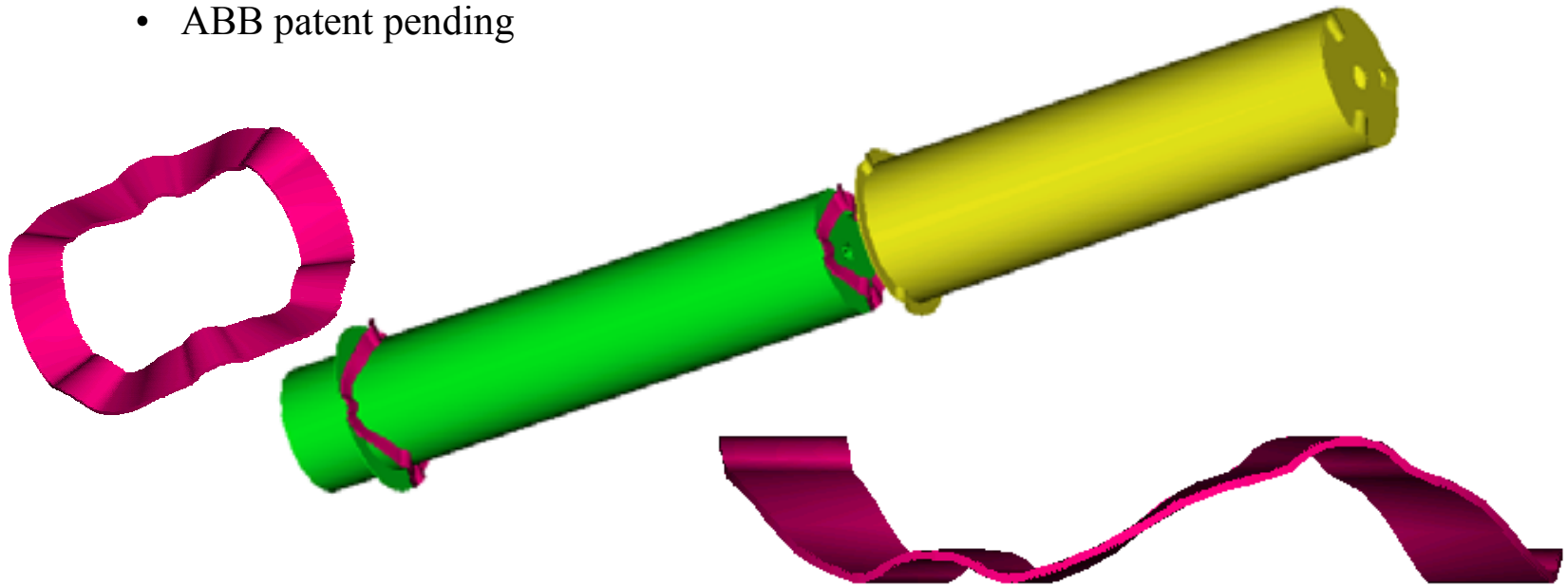
Flexed

*U.S. Patent 5, 678, 944



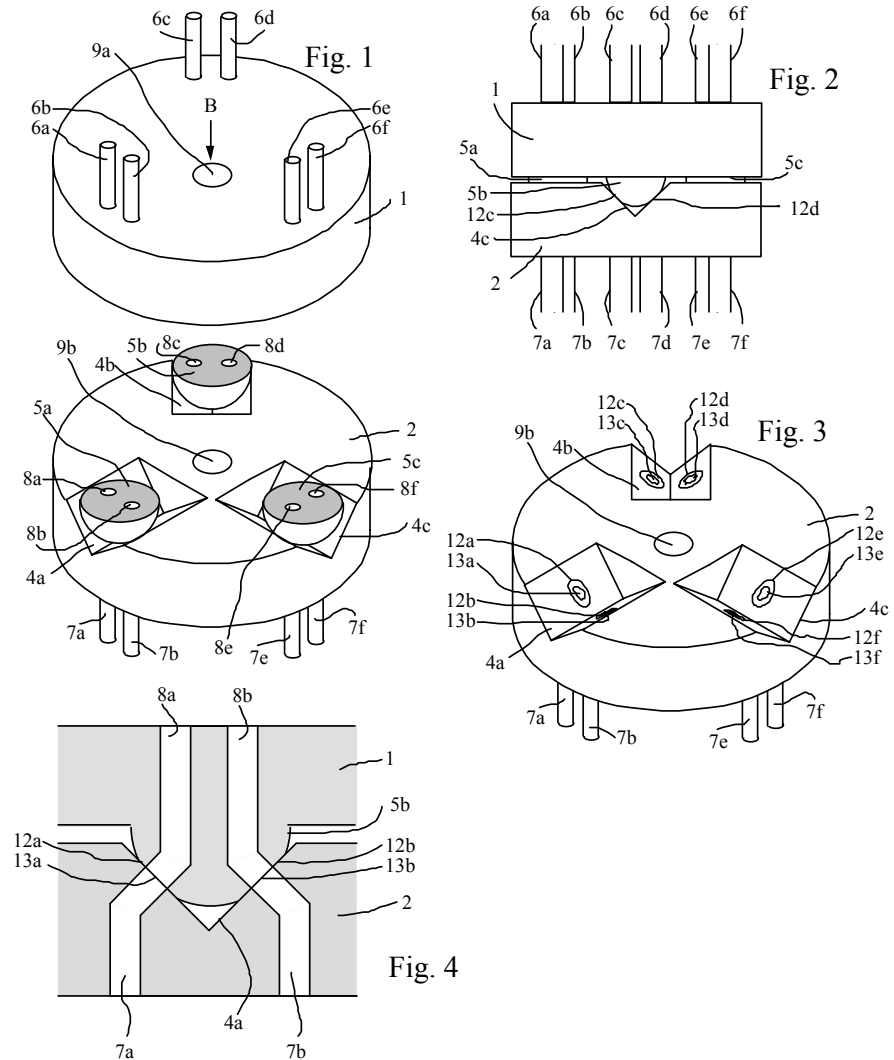
Example: Kinematic Wavy Spring Washer

- How to achieve compliant kinematic coupling effect for very low cost?
 - Form the elements into spring steel to form a *Kinematic Wavy Spring Washer*
 - Enables alignment while providing compliance between elements, OR
 - Enables kinematic coupling between elements with simple Vee grooves
 - Application of preload allows gap to close to create face-to-face loading condition for very high load capacity
 - ABB patent pending



Example: Kinematic Fluid Coupling (KFC)

- The KFC utilizes the Hertz contact area as a precision metal-to-metal seal for fluid or electrical connections



US Patent #5,683,118



Potential Medical Applications

What do you think?

- Is there a need for rapidly precisely coupled medical instruments?
- What about a robot with changeable end effectors that is coupled to an MRI unit?
-



Conclusion: Know Your Constraints!

- “Kinematic Design”, “Exact Constraint Design”.....the issue is:
 - KNOW what is happening in the system
 - Manage forces and deflections
 - Know when “Elastic Averaging” should be used
 - Know when “Kinematic Design” should be used
- To be robust and well-engineered, systems **MUST** be subject to a sensitivity analysis:
 - Accuracy and repeatability of motion
 - Constraint
 - Effects of variations on stress, deflection.....

