An Optocoupled Poseable Ball and Socket Joint for Computationally Enhanced Construction Kits

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***Abstract*—We present a novel design for connecting pieces of a computationally enhanced construction kit, an optocoupled ball and socket joint. Unlike other existing connectors, our joint is poseable and allows both the topology and dynamic configuration of a kit assembly to be sensed. We provide a survey of existing computationally enhanced construction kit connectors and describe the technical details of our design.**

I. Introduction

As microprocessors and wireless communication technologies become cheaper, smaller and more robust the vision of robotic construction kits with computation embedded in every piece is rapidly becoming feasible. This vision has been pursued by two communities: researchers in tangible interaction have built construction kits to explore input modalities [1]–[3]; and researchers in modular robotics have built kits to support rapid construction of robots [4]–[6].

Researchers in both of these communities have had to overcome similar technical hurdles. One of the most technologically challenging aspects of building a computationally enhanced construction kit is developing a connector that provides some or all of the following desiderata:

1) The connection should be mechanically robust.
2) It should provide a communication link.
3) It should provide power.
4) It should sense the topology of the connection (it should be able to detect which piece it is connected to).
5) It should sense the dynamic configuration of the connection (if the connector is not keyed so that two pieces can only be attached one way, it should be able to detect the current geometry).
6) It should provide a wide range of motion.
7) The connector should be poseable (once two pieces of the kit are attached, it should be possible to adjust their dynamic configuration, and the pieces should hold that configuration until they are adjusted again).

We present here a novel connection mechanism for computationally enhanced construction kits, an optocoupled poseable ball and socket joint (Figure 1), that provides all of these desiderata except power transmission, developed for our Posey computationally enhanced construction kit [7]. We will first review existing computationally enhanced construction kit connectors and the technologies they utilize, next we will provide the details of our design and finally we conclude with a discussion of the relative advantages of our system.

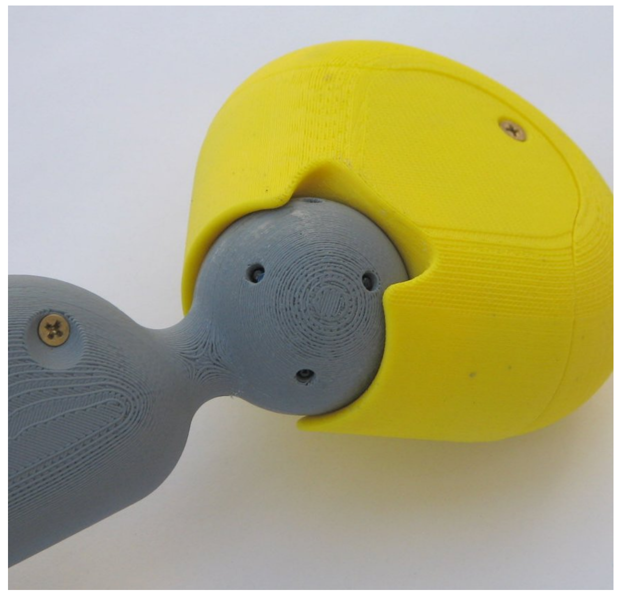


Fig. 1. Detail of optocoupled ball and socket joint of Posey construction kit.

II. Related Work

A. Existing Construction Kit Connectors

The design of existing computationally enhanced construction kit connectors varies widely depending on the kit's intended use. Table I shows which of the desiderata discussed above are provided by each of the connectors described below.

Monkey™, a specialized input device for virtual body animation [8], is not exactly a construction kit but demonstrates the sort of interaction that many kits aspire to. The segments of a Monkey™skeleton are connected with rotational potentiometers to read the figure's dynamic configuration.

Only a few pieces of a **Topobo** [9] kit have embedded electronics, but each of these pieces has a specialized keyed socket that not only senses its dynamic geometry and is poseable but is also actuated with a servomotor and will replay an animated pose once it is set.

Triangles [2] have permanent magnets on each edge of the triangular panels to form a mechanical connection and electrical contacts to transmit data and power. The Triangle connectors have a rotational degree of freedom that is not directly sensed, but can be inferred from the resulting topology.

The Self-Describing Building Blocks [1] connect with a 2x4 array of male power jacks on top and female jacks on the bottom, arranged like a Lego^{TM}brick. Each jack provides both a data connection and either power or ground.

ActiveCubes [10] have mechanical and electrical pins on each face that are keyed to allow cubes to be connected in only one orientation.

Speech-Enabled Alphabet Blocks [11] send data packets over an infrared optocoupled serial connection to build up words from the letters on the top face of the blocks and then speak the word out loud. They do not explicitly sense topology and do not mechanically connect.

roBlocks [12] are cubes that latch magnetically like the Triangles, and detect orientation through redundant data connections like the Self-Describing Building Blocks.

Senspectra [3] is a hub-and-strut kit with bendy struts with a headphone jack at either end to connect to static hubs. The jacks transfer power and detect the topology of the model. Each strut also has a bend sensor to determine the degree but not the direction of bending.

Odin [4] is a hub-and-strut modular robot kit whose struts have internal ball-and-socket joints at either end. Some of the struts may be actuated to extend their length. These struts connect to static spherical hubs that each have twelve keyed mechanical connections that also connect to form power and signal buses. Detecting topology and configuration were not among the design goals for this kit, but it would be straightforward to add topology detection by addressing the hub connectors.

CKbot [5] is a robotic cube with four faces with hermaphroditic connectors, and an internal degree of freedom that rotates one face relative to the other three. The basic connector has a bolt pattern to provide a mechanical connection and uses a standard header pin to provide power and communication buses. There is also a magnetic connector that allows modules to be quickly connected and disconnected, and communicates over an infrared serial optocouple. This two-connector design allows smaller groups of modules to share a power and communication bus and be connected together into larger configurations with the magnetic connectors. The topology and configuration of each connection are detected as well as the position of the internal degree of freedom. This information is transmitted to a design application on a host computer that allows gaits to be programmed by demonstrating key frames with the robot. However during this demonstration phase the modules do not hold their pose.

Molecube [6] is a robotic block with a hermaphroditic Lego^{TM}-style mechanical connector on each face, as well as a standard header-pin electrical connector. Like CKbot, this connection is static but each module has an internal actuated degree of freedom. The molecube connector is simple, straightforward to connect and provides a power and serial bus. Also like CKbot, topology and configuration of the connection as well as the position of the internal degree of freedom are all detected and transmitted to a design application on the host computer.

We are also involved in the construction of the **prismatic cubes** [13], self-reconfiguring robotic blocks that connect with an electrostatic comb [14]. Unlike the systems discussed above, the prismatic cubes' electronic latch must be actively triggered by the system once a mechanical connection has been made. A switch on the face of each module allows the cubes to determine when to activate their electrostatic combs. Like the CKbot magnetic connector, connected faces of the prismatic cubes communicate with an infrared serial optocouple. Through this connection the cubes are able to determine the topology of the current configuration. Due to the mechanical constraints of the modules they only connect in one orientation so that the geometry of the configuration can be determined from the topology and the state of each module's six internal prismatic degrees of freedom.

ATRON [15] is also a self-reconfiguring system with actuated latches, that connect by extending hooks to grab passive bars on the opposite module. Like CKbot and the molecubes, each module has an internal rotational degree of freedom. Like the prismatic cubes and CKbot's magnetic connector, modules communicate with an infrared serial optocouple. To address problems caused by infrared reflecting to neighboring modules as well as the directly latched neighbor a protocol for eliminating crosstalk during neighbor detection and local communication has been developed [16].

B. Spherical Position Sensors

While ball and socket joints allow a great deal of freedom in connecting and positioning an assembly of hubs and struts, tracking the spherical position of the ball in the socket is not trivial. Several sensing packages have been developed to address tracking the position of a spherical joint in robotics applications, but unlike our system they do not allow the joint to connect and disconnect, and do not provide a data transmission link.

Wang et al. [17] use an array of permanent magnets to drive a three degree of freedom ball joint, and use Hall effect sensors to track the ball's position by sensing the location of attached magnets. This is an impressive system for applications requiring an actuated joint but would require an outboard connector to be integrated into a construction kit, similar to Odin's captive ball-and-socket joint.

Stein, Scheinerman and Chirikjian's spherical encoder [18] holds more promise for construction kits. A black and white pattern is painted on the ball, and binary light sensors are positioned in the socket. The pattern is arranged so that the pitch, roll and yaw can be computed from the binary encoder readings. Although it might be straightforwards to embed this technology in a construction kit with a detachable ball and socket joint, the spherical encoder provides no mechanism to identify which ball is attached to a given socket.

TABLE I

DESIDERATA PROVIDED BY EXISTING CONSTRUCTION KIT CONNECTORS

	communication	**power**	**topology**	**configuration**	**poseable**
Posey	*serial through IR optocouple*	*no*	*through local serial*	*inferred from set of observed couples*	*socket tension maintains pose*
Monkey™	N/A	N/A	N/A	rotational pot	pot resistance maintains pose
Topobo	not without extra wire	no	no	some sockets have encoders	repeats animated pose with servo
Triangles	serial through electrical contact	magneto-electrical contact	through local serial	inferred from topology	no
SD Building Blocks	serial through power plug	pair of power/data plugs	through local serial	multiple data connections	no
ActiveCube	serial through electrical contact	electrical contact	through local serial	keyed	no
SE Alphabet Blocks	serial through IR optocouple	no	implicit linear topology	implicit in letter transmitted	no
roBlocks	serial through electrical contact	magneto-electrical contact	through local serial	multiple data connections	no
Senspectra	serial through electrical contact	electrical contact	through local serial	partial	bendable but cannot hold pose
Odin	serial through electrical contact	electrical contact	no	no	no
CKbot	serial through electrical contact or IR	on bolted faces	through local serial	multiple data connections; servo	only holds when actuated
Molecube	serial through electrical contact	electrical contact	through local serial	multiple data connections; servo	only holds when actuated
prismatic cubes	serial through IR optocouple	no	through local serial	inferred from topology	no
ATRON	serial through IR optocouple	no	through local serial	multiple data connections; encoder	no

Urata et al. have built a sensor [19] that tracks the spherical position of the ball using an array of apertures on the ball lit by an LED and a camera in the socket to track the movement of these apertures. Although their system only tracks the position of the ball, the scheme could be modified to also function as a serial data link by blinking the LEDs. The disadvantage is that its relatively expensive components make it prohibitive to place them in every joint of a construction kit – a camera in each socket and a microprocessor capable of performing image processing operations in real time in each hub.

III. MECHANICAL DESIGN

We were inspired by the ZOOB™construction kit[1] (Figure 2) to create a ball and socket joint for computationally enhanced construction kits. A ball and socket joint is simple to connect, mechanically robust and provides a wide range of motion. It can also be designed to hold its position, making assemblies easily poseable. By providing an array of LEDs on each ball and an array of phototransistors in each socket we maintain an optocoupled data connection and infer the dynamic configuration of the two pieces without requiring that any particular pair of features remains aligned across the connection.

[1]http://www.infinitoy.com/zoob/

Fig. 2. A model built with the ZOOB™construction kit.

A. Poseability

The socket has two jaws that grip the ball when it is inserted (Figure 1). The space between these jaws is slightly smaller than the ball, so that when the ball is inserted the jaws grip the ball and hold it in place, maintaining the current pose. The tolerances of this overlap are designed to take into account the material elasticity of the ball and socket. Our prototype is printed out of ABS plastic on a Stratasys Dimension SST fused deposition modeler, and to grip our 30mm diameter ball we have designed the jaws to encroach by 0.5mm on either side.

B. Range of Motion

Our ball and socket joint has a wide range of motion along three degrees of freedom, as illustrated in Figure 3b. The ball can roll all the way around in the socket. It can pitch up and down across a 200 degree range. And it can yaw 150 degrees from one side to the other. The yaw is constrained by the mechanical interference of the socket jaws.

IV. Optocoupled Connection and Position Sensor

To detect which strut connects to what hub and at what angle, we use arrays of optocoupled LEDs and phototransistors. Transmitting information locally between connected hubs and struts instead of through a wireless network makes it simple to determine connectivity. Unlike a direct electrical connection, there are no contacts on the surface of the pieces that could deliver a shock to someone who shorted the contacts. Whereas a small amount of slack between electrical contacts can cause problems, the LED and phototransistor need not touch to form a connection. Using infrared LEDs rather than visible light avoids problems that arise with interference from bright ambient light.

A significant limitation of our optocoupled connector is that each piece must carry its own battery, whereas electrical contacts could transmit power from a single source throughout an assembly. There are also several issues mentioned below that limit the accuracy of the angle sensing provided by our current prototype that we believe can be resolved in future designs.

A. Sensor Geometry

Each ball of each strut is equipped with an array of eleven infrared emitters, arranged in a regular tiling around the ball at the vertices of an icosahedron. (The twelfth vertex of the icosahedron falls within the neck.) Each socket of each hub contains an array of four sensors, each within a recess to collect light. The sensors are arranged within the socket so that each sensor sees at most one emitter at a given time, as in the current design the serial signals from two separate emitters would interfere. When a ball and socket are connected at least one sensor can see an emitter.

B. Optocoupled Data Transmission

When a sensor sees an emitter, an optocoupled serial data connection is formed. Each emitter blinks to continually emit a stream of three byte serial data packets. The first two bytes are the unique address of the strut containing the emitter, and the last is the index of that particular emitter. A parity bit for each byte and checksum byte for the packet are also sent to check for malformed packets, which are discarded.

Each sensor stores the strut address and emitter index it has most recently read. Sensors compare each new address and index read with the stored data. If it is different the sensor replaces the currently connected address with the new address and generates a wireless data packet with the new *(sensor, emitter)* couple information. To detect disconnection, if a data packet is not successfully read from a sensor within 5 attempts it resets its stored couple data to all zeroes and generates a wireless data packet to indicate that the sensor is no longer coupled to an emitter.

C. Detecting Topology

When a ball is connected to a socket at least one (and up to four, depending on local geometry) *(sensor, emitter)* couple is formed so that the strut directly transmits its unique address to the connected hub. When there is a change this couple data is sent wirelessly to the host computer so that it is straightforward to reconstruct the topology of the current model.

D. Detecting Position

As each sensor in each socket sends a data packet whenever it sees changes in the coupled emitter, driver software on the host computer can maintain a set of observed *(sensor, emitter)* couples for each socket. This data is used to infer the current roll-pitch-yaw position of the ball in the socket. A precomputed mapping from observed couples to positions is used to retrieve the possible roll-pitch-yaw values corresponding to the observed couple-set. The position most consistent with the preceding positions is chosen from these possible new roll-pitch-yaw values.

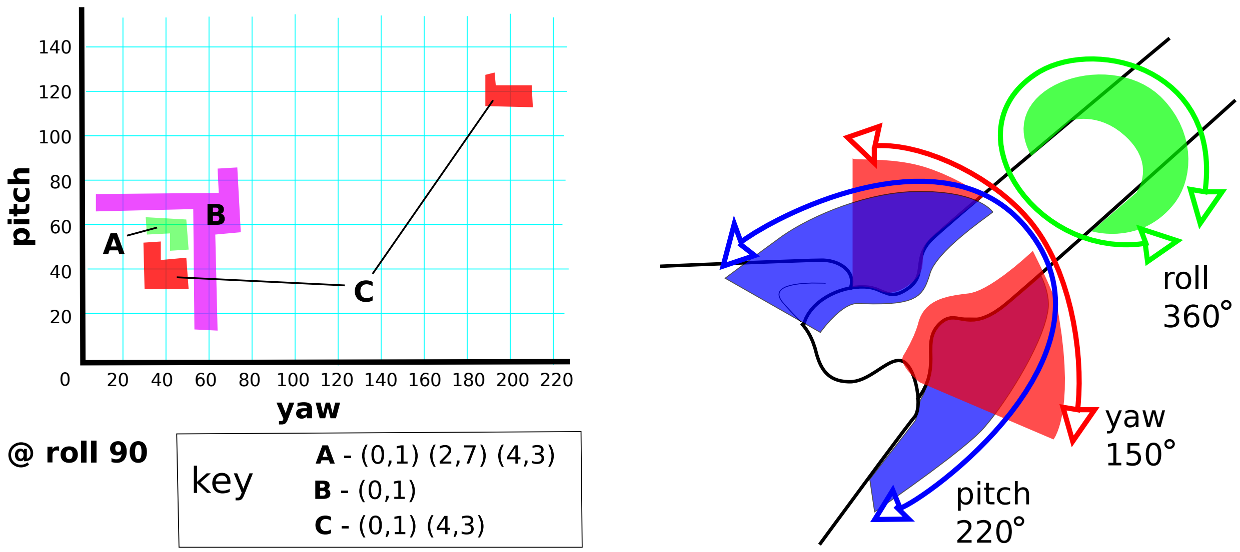
V. Data Collection

Data about changes in the state of an assembly of hubs and struts is collected through a wireless network directly linking each hub to a host computer. Each hub listens for data to be transmitted serially from connected struts. Each hub and strut has its own embedded processor and electronics to support this data collection network.

A. Processing Platform

Each hub and strut contains a custom circuit board with a AVR ATmega168 microprocessor. The ATmega168 has 23 digital input-output (IO) pins that directly drive the infrared LEDs on the struts and read the phototransistors on the hubs using internal pull-up resistors. We use its built-in UART port to communicate with the wireless transceiver in the hubs.

A 3.7 volt lithium-ion battery in each hub and strut powers the electronics. A charging and regulator circuit ensures that it is operated within safe voltage and current ranges, stepping down the output to a constant 3.3 volts. Figure 4 shows the electronics in each hub, excluding the phototransistor quads mounted in each socket that plug into headers on the hub motherboard.



(a) section through table showing 3 typical mappings of couple-sets to position

(b) diagram showing roll, pitch and yaw of strut

Fig. 3. Roll, pitch and yaw angles are inferred from the set of observed *(sensor, emitter)* couples.

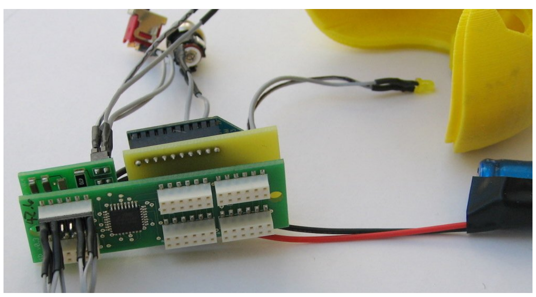


Fig. 4. Hub electronics includes an ATmega168 chip, Li Ion battery and charger circuit, Xbee radio transceiver, and connectors for four phototransistors (not shown) for each socket.

B. Local Optocoupled Serial Communication

Custom bit-banging code runs 22 LED serial transmitters in parallel on each strut and up to 16 phototransistor serial receivers on each hub. The ATmega168's built-in hardware timer triggers a callback to read or write bits from the IO pins. The serial receive code samples each input pin three times per bit and pads or drops bits as necessary to correct for drift. A parity bit for each byte and checksum byte for the packet are also sent to check for malformed packets, which are discarded.

As our bit-banging code transmits packets in parallel, the initial strut address segment of the infrared serial packet sent by neigboring emitters is identical, and only the last byte indicating the index of the emitter sending the signal (and the checksum byte) is different. It is the need to keep this one byte from interfering with neighboring bytes that forces us to place the socket sensors far enough apart to only see one emitter at a time. By altering our infrared packets to use three bytes to identify the current emitter, with a single bit to indicate each led rather than an integer, if one sensor received a signal from two or more emitters it could still distinguish how many and which emitters signals it was receving.

When a hub detects a change in one of its *(sensor, emitter)* couples it transmits a packet with the new data wirelessly to the host computer.

C. Wireless Data Transmission

Each hub has an XBEE wireless Zigbee transceiver connected to the UART port of the ATmega168. An XBEE Zigbee USB dongle connected to the personal computer receives the connection and configuration packet data. When the transceiver in each hub is powered on it scans the available wireless channels for the transceiver attached to the USB dongle and joins its network, creating a star network with the USB dongle at the center. When a data packet is written to the XBEE chip from the ATmega168 the XBEE waits until the microprocessor has finished and then sends the entire data packet in one Zigbee packet.

D. Angles from Observed LED-Sensor Couples

Depending on the roll, pitch, and yaw of a ball in its socket, as few as one and as many as four of the four socket sesnors will see an emitter. Thus each distinguishable 3-dimensional angle is described by a couple-set with up to four elements, in which each element consists of a pair:

```
(<sensor-id>, <emitter-id>)
```

For example, the connection-set:

```
[ (hub-7.2.0, strut-9.1.1),
  (hub-7.2.4, strut-9.1.3) ]
```

indicates that socket #2 of hub #7 is connected to ball #1 of strut #9, and that there are two *(sensor, emitter)* couples currently observed, sensor #0 with emitter #1 and sensor #4 with emitter #3. Upon receiving these connection-sets from each hub, the host computer uses a lookup table to translate a connection-set to a three dimensional (roll, pitch, and yaw) angle as shown in Figure 3. The above couple-set corresponds with the couple-set shown as *C* in the figure. The problem with the current symmetric layout of the emitters on each ball is that they do not always produce tightly grouped couple-sets. We would like for couple-sets to correspond to just a few closely spaced positions as shown with couple-set *A*. However sometimes a couple-set is consistent with a narrow but wide band of positions as with set *B*. And sometimes a couple-set is consistent with two disconnected position regions as shown with set *C*. We believe that couple-set regions like *B* and *C* could be avoided in future connectors by using a genetic algorithm to select emitter and sensor positions based on the fitness of their resulting couple-set layouts.

VI. Discussion

Our optocoupled poseable ball and socket joint, unlike other existing computationally enhanced construction kit connectors, is both poseable, reconfigurable and able to detect topology and dynamic configuration. This technology will enable construction kits with the expressiveness of Monkey™and Topobo to interface to applications on a personal computer or to program systems by demonstration.

The most significant limitation of our prototype is the current mapping from sets of observed *(sensor, emitter)* couples to possible positions. We believe that by changing our infrared packet structure to allow emitter signals to overlap and optimizing the sensor and emitter geometry to produce a more consistent mapping from observed couple-set to possible positions this technique can produce accurate three degree-of-freedom angle sensing.

The other limitation of optocoupled connections between modules is that each module must provide its own power. We believe the negative externalities of having a battery in each module could be mitigated by one of several technologies that will soon be available. For example, by using an inductive charging system embedded in the case the kit is stored in. When modules are placed in the case they would automatically turn off and charge inductively, and when they were removed from the case they would automatically turn on, obviating the current need for each module to have a power switch and charging socket. Or alternately the modules in a kit could be powered wirelessly as in [20], and could each have large capacitors rather than batteries.

On the positive side, with no exposed electrical connections the resulting modules could be extremely safe and robust. And the ball-and-socket connector is intuitive and simple to manipulate. With appropriate manufacturing processes this technology has the potential to allow inexpensive and robust spherical angle position sensing for both tangible input kits and modular robot building kits.

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