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Design of a Spherically Actuated Human Interaction Robot Head

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This paper presents the development of a mechanism for actuating a sphere holonomically about 3 degrees of freedom (DOF). The target application is a robot head for mounting inside a vehicle to provide a driver with companionship, location specific information, and other assistance, via head motions in conjunction with auditory communication. Prior art is reviewed and two designs are presented: One mechanism is located below the sphere and provides an unlimited range of motion (ROM), and the other is contained entirely within the sphere but has a limited range of motion. The latter is stable and easily mounted, provides a clean appearance, and is particularly suited to human interaction applications. [DOI: 10.1115/1.4006263]

Keywords: robot design, human robot interaction, product development

1 Introduction

Automotive design is seeking to move beyond traditional in-car navigation systems toward providing greater, more nuanced interaction with drivers, so as to encourage more positive outlooks and safer driving. To this end, Nissan research has developed a robotic agent (RA) to “connect the car and driver, engendering feelings of affection and trust” [1]. This consists of a robot head, shown in Fig. 1, mounted to the dashboard of the Pivo 2 concept car [2] along with a camera and microphone which monitor drivers’ facial expressions and voice patterns. By nodding, rotating, and illuminating its eyes, the RA coordinates with audio and video to

provide navigation and touristic information, responsive interaction with the driver, and general companionship. Similarly, interactive robots are finding particular application in elder care where companionship and assistance, such as medication reminders, are essential and a review of such is delivered in Ref. [3].

While there has been extensive research into developing humanoid robots, primary attention is given to their interactive capabilities, with the enabling mechanisms often receiving lighter treatment. It is posited that this may, on occasion, lead to larger than necessary, overly complex designs. Indeed, this was the case with the current prototype that featured an expensive, belt driven mechanism, larger than the head itself, located underneath it and inside the dashboard.¹ The mandate for this project was to develop a compact and economical alternative mechanism and proof-of-concept prototype, which could be easily controlled and mounted in diverse test locations within a vehicle cabin.

1.1 Background. Robots designed for human interaction represent a spectrum of detail and complexity. On one end are those with highly complex mechanisms, two of the best known being Honda’s Asimo [4], which can climb stairs, serve drinks, and play the violin, and MIT’s Kismet [5], shown in Fig. 2 top, which has a 15 DOF face designed to convey a wide range of emotions. The ROMAN humanoid face [6] from the University of Kaiserslautern, Germany was developed with the goal of creating a “very complex robot head able to simulate the facial expressions” along with a sensor system. Motion is achieved with six stepper motors which move the eyes, 11 servomotors which pull and push wires attached to the “skin,” one servo motor which opens the jaw, and four dc motors and encoders which operate the neck. The neck comprised a serial chain of revolute joints, which provide ± 60 deg of yaw about the vertical axis, ± 30 deg of both sideways roll and front-back pitch, and ± 40 deg of independent nodding. Hanson Robotics’ commercially available RoboKind [7] features a selection of rubber faces, including Albert Einstein’s, and a walking body. While ROMAN and other anthropomorphic robots seek to replicate the motions of a human face, Kismet’s designer Cynthia Breazeal recommends focusing on designing for “believability” rather than potentially failing at complete “realism.” Furthermore, she has shown that an “infantile” appearance, with features such as large eyes and an oversize head, elicits a positive nurturing response. Taking this philosophy to the other end of the complexity spectrum is Keepon, shown in Fig. 2 bottom, a small robot with a one-piece, yellow foam rubber body designed as a therapy robot for autistic children. Underlying the lower half of Keepon’s rubber body are gimbals which are actuated by four wires and dc motors in the base. The ROM is ± 180 deg of yaw, ± 40 deg of nodding pitch, ± 25 deg of sideways roll, and 15 mm up and down bounce. In designing Keepon, Hideki Kozima from Japan’s National Institute of Information and Communications Technology postulated that autistic children may be “overwhelmed by the flood of sensory stimuli” during interpersonal interactions and thus might “engage more comfortably in positive social behavior with a robot like Keepon, designed as the simplest possible social creature” [8]. In addition, Kozima warns that controlling a large number of DOF in convincing manner is challenging and may result in a mechanism that technically interesting but distracting and that trying too hard to humanoid may be perceived as “uncanny” [9].

1.2 Functional Requirements and Specifications. In discussions with Nissan, the following broad functional requirements for the robot head were identified:

- (1) consist of a 120 mm diameter sphere with a substructure no larger than 200 mm square by 100 mm high

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¹Unfortunately, a confidentiality agreement between Nissan and the mechanism’s fabricant prevents inclusion of more detail.



Fig. 1 Nissan PIVO, detail of RA prototype on dashboard [1] and maximum admissible dimensions specified by Nissan

- (2) provide 3 DOF holonomic motion including nodding and tilting (pitch and roll) and rotation (yaw)
- (3) have a durable and safe exterior and be secured
- (4) embody a minimalist design that is “cute” rather than humanoid

First, the current design’s form factor, with a large underlying mechanism, was identified as a limitation. Space within an autom-

bile’s dashboard is at a premium and the dimensions provided were the absolute maximum allowed; a smaller drive mechanism would increase the number of potential mounting locations. Second, while the initial prototype could only rotate in yaw and pitch forwards and backwards, it was decided that full expressiveness also required roll motion; however, no further DOF were seen as necessary. According to Tilley [10], the human skull can pitch 60 deg to the rear and 30 deg to the front (increasing to 60 deg if cervical spine bending is included) and roll ± 54 deg. A ROM of ± 40 deg in both roll and pitch was selected as reasonable and in keeping with comparable humanoid robots. About the yaw direction a human head can turn ± 60 deg (with the shoulders an additional 25 deg); however, the robot would require at least ± 180 deg to allow it to go from facing forwards, like a passenger, to looking completely backwards. To maintain realism, it was decided that the robot should be prevented from spinning completely around without limit; rather it would “unwind” back from each rotation. Naturally, all motions needed to be singularity free. Third, for any robot that interacts with people, safety is paramount; thus, the drive mechanism needed to be completely enclosed, with no pinch points, and the entire robot firmly affixed so that it would not become a projectile during a crash. A single mounting point of attachment was preferred in order to maximize mounting flexibility. In addition, the robot’s face should be durable and touchable, particularly to resist children’s (sticky) fingers. The need to resist deliberate abuse, e.g., punched in the case of road rage, was also identified, but considered outside the scope of this design project. Finally, the minimalist design requirement took its cues from the existing prototype’s design, Keepon’s styling, and Breazeal’s advice. Additionally, it was important to balance expressive interaction with the potential for distraction.

2 Spherical Actuation Methods

The selection of a spherical geometry suggested two principal actuation methods: ball wheels and gimbals. Prior art was researched for each and two prototypes constructed and evaluated. The following provides a review of the applicable art, with respect to the concepts explored.

2.1 Ball Wheels and Ikon Wheels. Ball wheels consist of a sphere within a cradle that permits it to rotate with at least two degrees of freedom, so as to facilitate material transfer across the ball or enable something mounted to the cradle to roll about freely. The dimension sketch, shown in Fig. 1, suggested a ball sitting on top of a cradle and looked similar to a set of globes designed by Henry Dreyfuss Associates and presented to Prime Minister Churchill and President Roosevelt during WWII. Shown in Fig. 3, the 750 lb globe is supported, so as to rotate freely in any direction, upon a low-profile cradle consisting of three hard rubber balls, each able to rotate about two axes and mounted within a swiveling steel cup [11].

The MIT thesis of West [12] describes the development of a new class of ball wheel for a smooth rolling, omnidirectional wheelchair. West undertook a comprehensive review of existing designs and four mechanisms considered in his thesis are reproduced in Fig. 4. In mechanism (a), the ball rests upon three spherical bearings, the minimum number of contact points necessary to contain it. Spherical bearings, however, while providing passive support for unrestricted motion, do not lend themselves to position controlled actuation, a conclusion also reached by ROMAN’s developers. Configuration (b) replaces the bearings with three rollers. These could be powered to actuate the sphere; however, any component of an arbitrary rotation, not coplanar with the axis of a given roller, would cause slip along that roller and a loss of control. Configuration (c) overcomes this problem by providing an extra degree of freedom for one of the three rollers, thus allowing the ball to be controlled about the fixed rollers’ 2 DOF. In West’s final design (d), a ring of rollers, which itself is free to rotate, contains the ball while a single roller affixed to the chassis

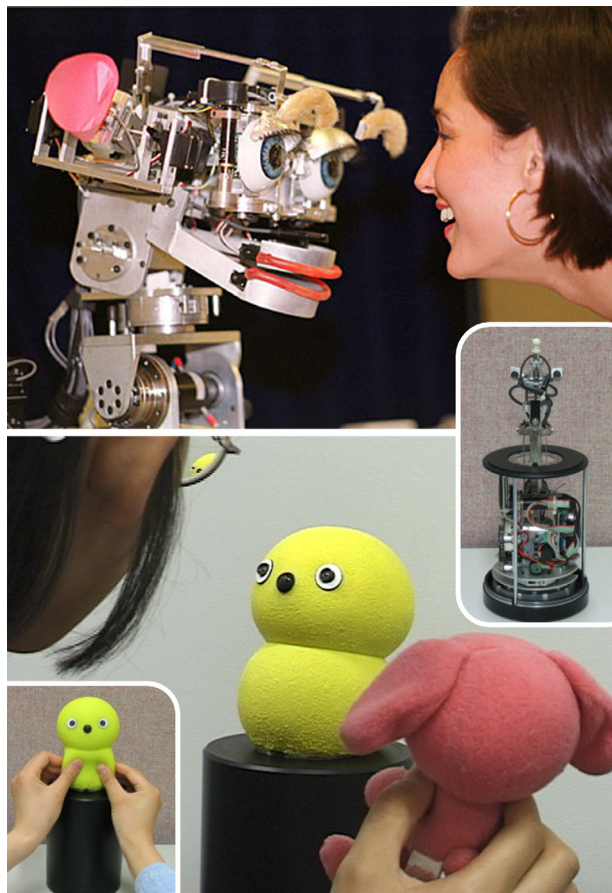


Fig. 2 Top: Kismet, photo by Donna Coveney, MIT Publishing; bottom: Keepon making eye contact with insets showing mechanism and deformable body, photos courtesy of Hideki Kozima



Fig. 3 Top: “President Roosevelt and his globe,” 1942, photo courtesy of FDR Library; bottom: support base and mechanism detail showing ball rotating in swiveling cup, photos courtesy of Sylvia Sumira

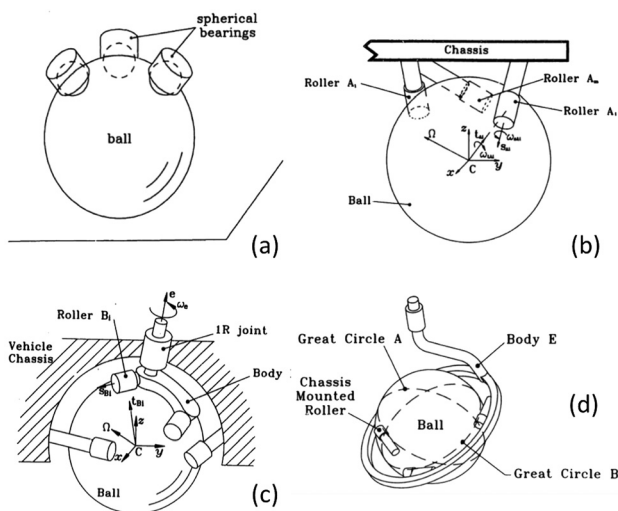


Fig. 4 Selected ball wheel mechanisms: (a) ball supported by spherical bearings which permit free motion; (b) ball supported upon three rollers; (c) modification with two pivoting rollers; (d) alternate design with an extra degree of freedom; images excerpted from Ref. [12]

drives the ball about one DOF. Three of these can move and control a vehicle about 3 DOF. However, despite investigating ball wheels extensively, no method of actuating a single ball about 3 DOF with only three actuators was identified. It can be hypothesized that with redundant actuators 3 DOF holonomic control might be possible.

A more elegant solution would be to employ a roller that could provide traction in one direction while permitting crosswise motion. Shown in image (a) of Fig. 5, the omni (omnidirectional)

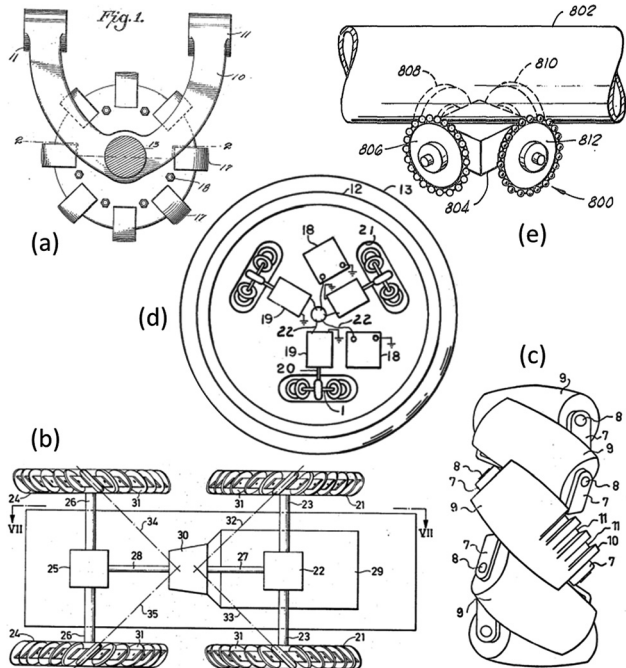


Fig. 5 (a) Omni wheel design from 1919 [13]; (b) Ilon's vehicle employing wheels with angled rollers which create sideways tractive forces [14]; (c) Ilon wheel with barrel shaped rollers for smooth motion [15]; (d) vehicle having three omni wheels [16]; (e) Omni wheels driving a curved surface [17]

wheel is an old design, comprised a wheel with a series of rollers spaced around its circumference that enable traction in one direction and free rolling in the perpendicular direction [13]. A drawback to this design is that the broken circumference introduces vibrations as contact passes from roller to roller. The Ilon (or Mechanum) wheel is a refinement by Swedish inventor Bengt Ilon having barrel shaped rollers at a 45 deg angle that also generate sideways tractive forces as the wheel is turned [14,15]. The tapered rollers overlap slightly, describing an uninterrupted circle, and thus roll smoother; however, the contact point shifting from side can still induce vibrations.

By employing a minimum of three omni wheels, an omnidirectional vehicle, capable of holonomic motion, can be built. With respect to an actuated sphere, La [16] suggests the possibility of omni wheels driving a surface and Bradbury [17] specifically mentions using them on a spherical surface. These two patents together with the “President’s Globe” inspired the first prototype concept—a ball seated in a cradle and driven by omni wheels, described in Sec. 3.1.

2.2 Gimbals. As an alternate strategy gimbals were considered and a selection is shown in Fig. 6. Two possible drawbacks to gimbals are gimbal lock and the challenge of actuating the inner ring(s). The former was not a severe concern, given the head’s limited desired ROM, and to address the latter mechanisms were identified whereby two of the actuators remained stationary. Three pertinent patents, originating from the radar industry, were identified: The first [18] by Flint for general electric describes an elegant design which orients a gimbal in 2 DOF via a flexible, differential chain, driven by two motors on the base of the yoke. The third DOF is obtained by rotating the entire yoke, thus yielding a compact and completely secured design. The second [19] by Spiecher for General Dynamics implements a cable drive (or dual rack and pinion) and adds rollers which stabilize the outer half ring. In the third [20], Spiecher compacts his mechanism so that the outer ring is eliminated and all the drives are placed within a single ring and below the pedestal. Neither of the latter two patents feature a

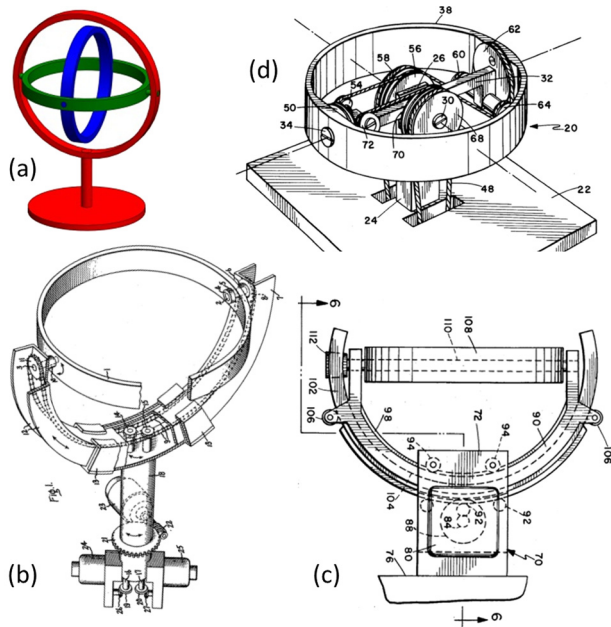


Fig. 6 (a) Gimbal mechanism; (b) three DOF chain driven mechanism for General Dynamics [18]; (c) “Differential Drive Rolling Arc Gimbal” for General Dynamics [19]; (d) refinement of previous design, “Differential Drive Pedestal Gimbal” [20]

rotating yoke and, thus, lack the third degree of freedom. These patents combined led to the second concept design, whereby the entire mechanism is contained within the sphere, described in Sec. 3.2.

3 Mechanism Design

3.1 Omni Wheel Drive Prototype. In the first prototype, shown in Fig. 7, three omni wheels are spaced 120 deg apart and tilted so that each lies in a plane that slices the sphere into hemispheres; this way the sphere will rotate around its center point. A sketch of the system, indicating the pertinent angles and dimensions, is also shown in Fig. 7. Using the location of wheels 0, 1, and 2, with respect to the center of the sphere, a set of scaling factors is determined that convert desired roll, pitch, and yaw displacements and velocities into motor commands. The three wheels are driven open-loop with stepper motors, a hobby controller and a test interface implemented in Visual Basic.

3.1.1 Structure and Actuators. This proof-of-concept prototype was constructed primarily of commercially available components including: a 152.4 mm (6 in.) diameter hollow steel sphere weighing 1.5 kg, three 50.8 mm (2 in.) diameter omni wheel with rubber coated rollers, and low cost (\$20) 12 V permanent magnet stepper motors fitted with 50:1 gearboxes.² The base was fabricated from folded sheet metal and, excluding the wheels’ projection, measures 153 mm (6.02 in.) wide and 64 mm (2.52 in.) high. The sphere and base size were on the order of the target specifications. Motor step size was 7.5 deg and maximum speed was 500 rpm; with half stepping, the gearbox, and a 3:1 wheel to sphere ratio, the head motion had an expected maximum resolution of 0.025 deg and speed of 3.3 rpm (20 deg/s). Resolution was an order of magnitude higher than necessary, while speed was much slower than specified. The motors were driven with a Phidget1062³ four-axis stepper controller designed for hobby use; it is part of a larger family of plug-and-play USB sensing and control devices supported by an extensive API library with drivers for all major operating systems and programming languages. After implementation it became apparent that controller featured an 8

²Anaheim automation: www.anaheimautomation.com

³Phidgets products for USB sensing and control: <http://www.phidgets.com/>

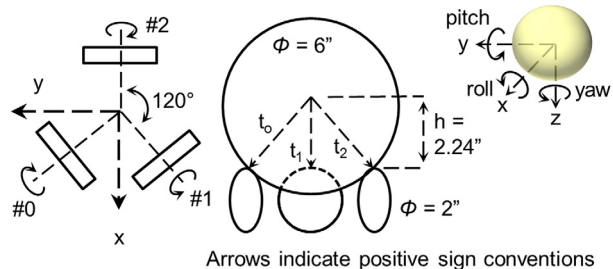
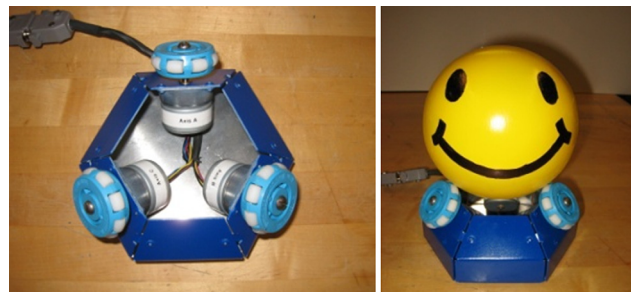


Fig. 7 Omni wheel prototype and geometry; arrows indicate positive direction conventions

bit processor that was only capable of commanding 383 half steps per second; this limited the actual maximum velocity to 9.6 deg/s.

3.1.2 Control. For prototyping purposes, a simple control strategy was implemented based on a fixed x–y–z coordinate system with roll, pitch, and yaw motions that were defined in the clockwise direction about these axes. Yaw specifies the direction that the head is looking, i.e., straight forward (0 deg), left (–80 deg), or right (+80 deg), pitch whether the head is looking up or down and roll a tilt to one side. Each wheel’s contact point with the sphere is identified by a unit vector, t_0 , t_1 , and t_2 , pointing from the sphere’s center. As shown in Eq. (1), these are found using the 120 deg separation between the rollers, the height (h) from the contact points to the center of the sphere, and the sphere’s radius (l). These three unit vectors are arranged in a 3×3 matrix, multiplied by three scalars, and set equal to a unit vector pointing along the x-axis, as shown in Eq. (2). Solving this system of equations for the scalars (R) yields each wheel’s relative contribution to roll motion (about the x-axis). This is repeated for pitch (P) and yaw (Y) motion scalars and the particular solution for this prototype’s geometry is given in Eq. (3)

$$\begin{aligned} t_0 &= \frac{d \sin(30)}{l} \hat{i} + \frac{d \sin(30)}{l} \hat{j} + \frac{h}{l} \hat{k} \\ t_1 &= \frac{d \sin(30)}{l} \hat{i} + \frac{d \sin(30)}{l} \hat{j} + \frac{h}{l} \hat{k} \\ t_2 &= \frac{d}{l} \hat{i} + 0 \hat{j} + \frac{h}{l} \hat{k} \end{aligned} \quad (1)$$

$$\begin{bmatrix} t_0 \hat{i} & t_0 \hat{j} & t_0 \hat{k} \\ t_1 \hat{i} & t_1 \hat{j} & t_1 \hat{k} \\ t_2 \hat{i} & t_2 \hat{j} & t_2 \hat{k} \end{bmatrix} \begin{bmatrix} R_0 \\ R_1 \\ R_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \text{stepper}_0 \\ \text{stepper}_1 \\ \text{stepper}_2 \end{bmatrix} = \begin{bmatrix} 0.5 & 0.867 & 0.447 \\ 0.5 & -0.867 & 0.447 \\ -1 & 0 & 0.447 \end{bmatrix} \begin{bmatrix} \text{roll} \\ \text{pitch} \\ \text{yaw} \end{bmatrix} \quad (3)$$

These nine factors convert a desired roll, pitch, and yaw to servo motor displacements; for example, in order to roll the head +40 deg to the right, the controller commands wheels 0 and 1 to turn +25

deg and wheel 2 to turn 40 deg. The speed of each wheel is similarly scaled and a trapezoidal profile applied. A practical alternative control strategy would be to place a unit vector at the origin and orient it to indicate the direction in which the face should point; comparing this with the previous direction vector would yield the necessary motions.

3.1.3 Evaluation. This prototype clearly was able to provide unrestricted 3 DOF holonomic motion; however, fundamental flaws were identified which prevented it from meeting the desired specifications: First, slippage between the rollers and the ball represented a loss of control. To address this, higher friction ball or roller materials could be implemented and magnets added below the ball, or incorporated into the rollers, to provide preload force. Alternatively, a plastic ball could be employed with a freely rolling metal sphere placed inside that would be attracted to the magnet. Second, the unsecured sphere failed to fulfill the safety criterion. Third, the omni wheels' discontinuous circumference introduced unacceptable vibrations. The possibility of modifying Ilon's wheels' barrel shaped geometry to roll smoothly against a sphere (as opposed to as flat surface) was considered, but not prototyped since the shifting contact point would still have introduced (lesser) vibrations and added a control challenge. Finally, no straightforward method of absolute position sensing was identified that would enable homing of the sphere, independent of wheel position. Optical tracking, such as used in computer mice, was considered; however, this provides only incremental position information. Therefore, while this prototype demonstrated a compact method of actuating a sphere with no limitations about 3 DOF, it was not further pursued. It might still be of interest as a 3 DOF actuated ball wheel.

3.2 Differential Drive Prototype. Learning from the failings of the first prototype, the radar-inspired designs offered a compact mechanism, whereby the sphere would be intrinsically secured, and a method of actuation contained entirely within the sphere, which would maximize flexibility in mounting locations. The pedestal mounting, reminiscent of a human neck, would restrict motion; however, this would not be a significant hurdle, provided that the target ROM could be achieved. This led to a two part design concept: (1) a differential comprised four bevel gears and driven by two servos that actuate a shaft, connected to the inside of the sphere, in pitch and roll; and (2) a frame supporting the differential that is rotated in yaw about a mounting shaft exiting from the base of the sphere. Shown in Fig. 8 is the first proof-of-concept prototype.

3.2.1 Structure and Actuators. As before, the mechanism was assembled using commercially available components. The head comprised a 6 in. (152.4 mm) diameter, hollow plastic sphere of negligible weight that was sliced into upper and lower hemispheres. The mounting shaft and wiring harness projected through a hole cut in the lower hemisphere. Inside the sphere was a sheet metal frame which supported three hobby servos. Two servos were axially aligned, with bevel gears fitted directly to their shafts. Passing between these was a shaft, the ends of which were connected to the inside the sphere where the "ears" would be. Two mating bevel gears were fitted to this with one pinned in position and the other free spinning on a bushing, but constrained axially. Thus, the gear mesh constrained the sphere to the frame while effecting 2 DOF motion. The third servo was placed at the base of the frame and connected directly to the mounting shaft.

Hobby servo actuators are commonly used in humanoid robots for their compactness and ease of mounting; an extensive search indicated that there is no off-the-shelf equivalent for a high torque solution in a very small package, with integrated position control electronics. The selected HiTech⁴ HS-5245MG "digital"⁵ servos

⁴HiTec RCD USA: <http://www.hitec.com/>

⁵The "digital" servos offer slightly greater torque, a few programmable parameters, and a slightly faster control loop; though testing demonstrated minimal advantages and they were not used in the second prototype.

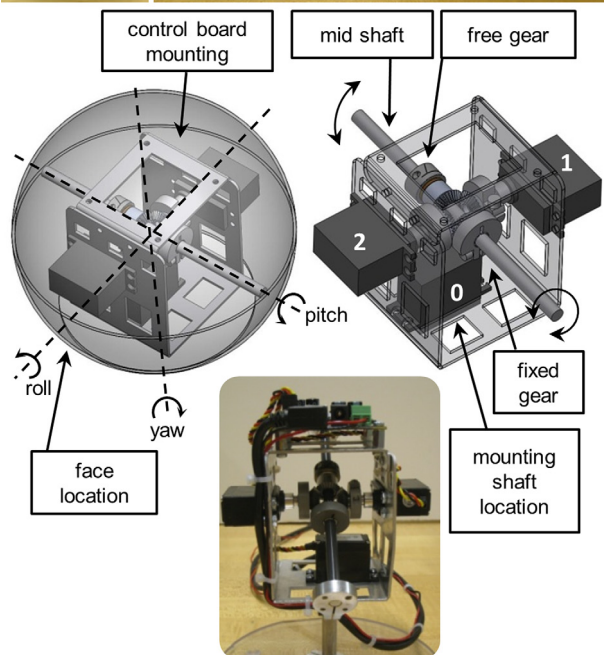
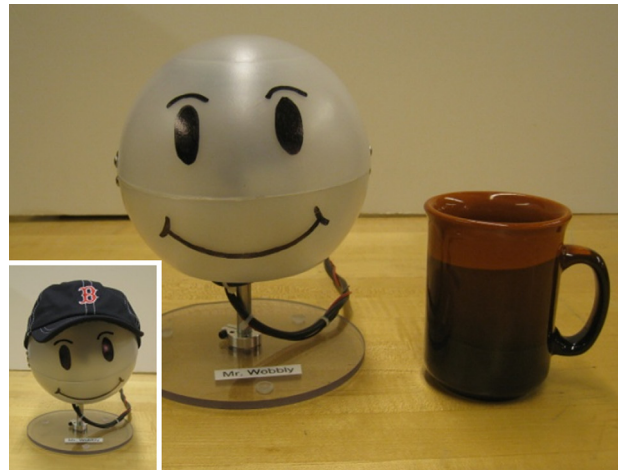


Fig. 8 Differential drive prototype #1. Arrows indicate positive direction conventions. In the roll and pitch directions, the sphere tilts and the entire structure rotates about the mounting shaft in yaw.

(~\$50), provide 5.5 kg cm (53.9 N cm) stall torque, can move 60 deg in 0.12 s at 6 V, with a maximum rotational displacement of 180 deg, and have a 32 × 17 × 31 mm "mini" package. Smaller "micro" servos do not have ball bearings and metal gears and, in the absence of manufacturer's loading specifications, the larger servos were seen as a safer choice.⁶ (It is hoped that servo manufacturers will someday become aware of the market for better specified products.) Three wires connect to the servo, power (+6 V, 1.5 A), ground, and signal, absolute position is monitored internally by a potentiometer connected directly to the output shaft and the desired position is communicated via a pulse width modulated signal where width indicates desired position.⁷ Mounted to the sheet metal frame above the differential is a Phidgets 1061 eight-axis hobby servo controller. Servos' internal electronics are designed to attain the commanded position as fast as possible; this

⁶Despite their products being increasingly used in prototyping, servo manufacturers continue to provide only limited and unclear performance specifications.

⁷Pulses are delivered to each servo every 20 ms with a pulse width of 0.6 ms indicates a desired position of -90 deg (anticlockwise when facing the servo shaft), 1.5 ms the center and 2.4 ms +90 deg.

controller executes a motion profile by generating position commands progressively, based on inputted endpoint and desired velocity and acceleration. In order to ensure that the servos would provide sufficient torque, the moment of inertia about the yaw axis, where a single servo rotates the sphere, the entire structure, and all three servos, was estimated from the solid model to be $8.21 \times 10^5 \text{ g mm}^2$. Using half the stall torque ($\tau = 27 \text{ N cm}$), the time to accelerate (t_a) to a speed of 100 deg/s ($\Delta\omega = 1.745 \text{ rad/s}$) was found to be nearly instant, indicating that the selected servos were significantly overpowered

$$\frac{\Delta\omega t_a}{\tau} = t_a = 5.3E^{-3} s \quad (4)$$

3.2.2 Control. The same control strategy, based on a fixed coordinate system, was applied to the second prototype and the test interface adapted to communicate with the servo board. When powered up servos conveniently self-home, so once the prototype was assembled and correctly adjusted with small “trim” offsets, no startup procedure was needed. As seen in Fig. 8, axis 0 controls yaw motion and axes 1 and 2 together pitch and roll. The following equations determine the commands sent to each servo as a function of the desired positions

$$\begin{aligned} \text{servo}_0 &= \text{yaw} \\ \text{servo}_1 &= \text{pitch} + \text{roll} \\ \text{servo}_2 &= \text{pitch} - \text{roll} \end{aligned} \quad (5)$$

Turning servos 1 and 2 together, i.e., servo 1 in the positive direction and servo 2 in the negative direction, causes the shaft to tilt longitudinally and the head to roll. Turning them in opposite directions rotates the shaft axially and the head pitches. For example, in order to execute 40 deg of roll and 40 deg of pitch simultaneously, one servo must move 80 deg off its center position, almost its full 90 deg off-center ROM.

3.2.3 Evaluation. This prototype demonstrated the feasibility of using a combination of four bevel gears mounted in a rotating frame to actuate a sphere about three directions, with the entire mechanism and control electronics contained within the sphere. An approximate $\pm 40 \text{ deg}$ ROM was achieved in the pitch and roll directions, a function of the servos’ limits and the size of the hole in the lower hemisphere through which the mounting shaft projected. In the yaw direction, the sphere was able to rotate the full $\pm 90 \text{ deg}$ permitted by the servo, less than the specification.

The servos performed with sufficient speed and torque, however, several limitations were evident. First, the exact internal control scheme implemented by the servos is not documented; however, it does not appear to comprise any damping or integration. Instead, it appears to be a very stiff “bang–bang” control scheme, whereby full torque is applied to small displacements leading to jerky motion. In addition, servo drift and slightly unequal calibration from servo to servo were noticed. The metal gears performed reliably although they were noisy, and backlash in the gear train was estimated at 0.5 deg . Thermal management is also a concern with servos which, if commanded to an unreachable position, e.g., against a hard stop past 90 deg , will briskly overheat and fail.

Based on testing, this design was selected for further development and the construction begun of a more robust prototype, suitable for in situ testing. Necessary changes for the next prototype included increasing the yaw ROM with gearing, decreasing the sphere size to meet specification, stiffening the structure so that it could support a preload of the gear mesh to remove rattle, addition of a slip ring and routing of the wiring harness through the mounting shaft, better stabilization of the mounting shaft, and fitting of a flexible cuff to close the lower hemisphere around the mounting shaft.

3.3 Final Prototype. First, the ball was replaced with custom hemispheres, 3D printed in Watershed 11120 stereolithography

(SLA) resin⁸, of diameter 130 mm , just slightly bigger than the target specification. The hemispheres closed from the front and back and were sized to fit tightly around the mechanism. With customized components and tighter packing, it would certainly be possible to meet the target size specification. The actuators were “downgraded” to HS-225 MG analog servos ($\sim \$28$) of the same size with slightly lower specifications, 4.8 kg cm (47.1 N cm) stall torque and a 60 deg transverse in 0.11 s ; however, no appreciable decrease in performance was noted. The sheet metal structure was replaced with machined aluminum components which facilitated proper alignment of the differential. A slight preload on the order of 15 N was applied to the gear mesh via a wave washer placed between the free gear and the shaft collar which restrained it axially; postassembly, this was found to have successfully reduced the backlash to the point that it could not be felt when wiggled by hand. To place the hemisphere seams at the sides, the mechanism and shaft were rotated 90 deg inside the sphere, resulting in sign changes in the control equations

$$\begin{aligned} \text{servo}_0 &= \text{yaw} \\ \text{servo}_1 &= -\text{pitch} - \text{roll} \\ \text{servo}_2 &= \text{pitch} - \text{roll} \end{aligned} \quad (6)$$

The shaft was significant source of instability in the previous prototype and, in order to address this, increase the yaw ROM and facilitate routing of the wires through the mounting shaft, the yaw servo was moved to the side and fitted with a large gear. The mounting shaft was then supported between two ball bearings, with a smaller gear in between that engaged the large gear. The resulting 2.1:1 gear ratio allowed the structure to yaw around the shaft in excess of 360 deg . Surmounting the mounting shaft was a Moog⁹ slip ring capsule, with the body was fixed to the structure and the rotor projecting into the shaft, thus enabling the head to turn freely without twisting.

A flexible boot, modeled on a gearshift’s covering, was fitted to the base of the sphere. It is designed to allow the sphere to pitch and roll while completely covering the hole in the base. The top is secured by a ring around the hole in the sphere and the bottom to a tube which surrounds the mounting shaft and turns with the frame; thus, the boot does not experience any twisting motion. However, as designed, it was found to bunch up and restrict motion. Alternatively, overlapping, curved sliding plates could be employed to enclose the sphere’s bottom.

Nissan’s original prototype featured illuminated eyes and, as seen in Fig. 9, the front hemisphere of this prototype was fitted with two blue light emitting diode (LED) eyes, controlled with a spare servo channel via a special adaptor.¹⁰ In addition, a miniature 2 W (4 W max) speaker, producing 80 dB , is placed in the mouth position. While in the original prototype sound was provided by stationary speakers, this was added to enable evaluation of user response to a moving sound source. Because the sphere moves relative the inside frame, these are connected to the control board by a flexible wire which adds significant complexity and is a potential failure point. In a future prototype, the eyes would be made translucent and LEDs affixed to the interior frame.

3.3.1 Evaluation. Evaluating the prototype mechanism with respect to the desired functional requirements indicated that the basic design was viable but testing showed that the instability problem was not entirely solved. Wobble in the bearings allowed the head to rock by $1\text{--}2 \text{ deg}$, corresponding to $2\text{--}3 \text{ mm}$ of sideways motion at the sphere top, and the yaw gears’ mesh was insufficiently tight allowing $2\text{--}3 \text{ deg}$ backlash. More interesting were

⁸DSM Somos printed by Vaupell Rapid Solutions: http://www.dsm.com/en_US/html/dsms/home_dsmsomos.htm; <http://www.vaupell.com>

⁹Moog components group: <http://www.moog.com/>

¹⁰This “RC switch,” manufactured by Firmtronics (<http://www.firmtronics.com/>) accepts power and signal from a standard three pin servo channel and in response to various PWM signals switches small loads on or off.

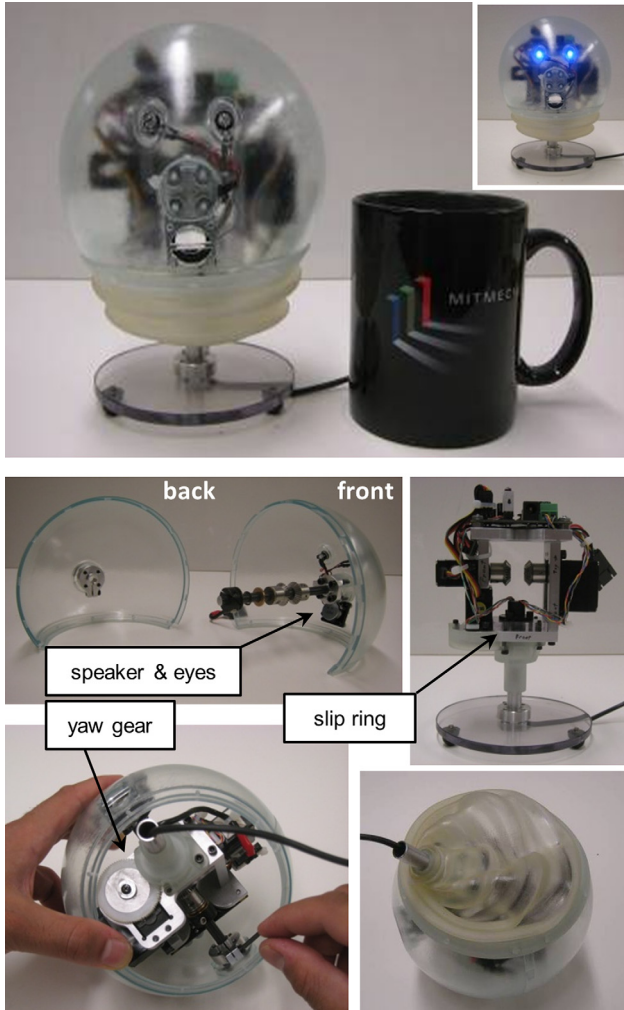


Fig. 9 Differential drive prototype #2. Mechanism and assembly are shown.

the dynamics which resulted from coupling the two servos together through the differential. Because of their stiff “bang–bang” control loops the servos were observed to effectively fight over the shaft. First one would detect a tiny offset, activate and move the shaft to the point that the backlash was taken out of both servos’ gear trains and then the other servo would detect an offset; the result being a visible and audible vibration at the end of each move. Gently wiggling the head until both servos were exactly in a neutral position was a temporary solution. A similar effect was observed in the yaw direction whereby with a little jiggle the head could be made to oscillate back and forth by 6–8 deg with the undamped servo providing a little “kick” at each side. Both these vibrations could be addressed with the addition of a spring preload or a softer servo control loop.

3.3.2 Future Work. Moving forward, the next step is to transition to custom designed components, which will result in cost and weight reduction, better control and increased reliability. As many metallic components as possible should be replaced with plastic; a lighter frame will reduce the moment of inertia and bevel and spur gears made of a self-lubricating material will reduce noise. The hobby servos can be replicated with dc gear motors and potentiometers, which remain a viable feedback mechanism for the limited ROMs, and a custom control board fash-

ioned to integrate with the frame. The boot should be redesigned to increase its range of motion, without bunching, or replaced with sliding plates. The yaw mechanism and the mounting shaft’s constraint will require thought in order to remove backlash and wobble. The current ranges of motion and speeds are adequate, but the accelerations and control parameters need adjustment and a control strategy must be implemented that accounts for the coupled actuators. The only inherently expensive component is the slip ring; a more economical solution would be to use a spooled ribbon cable, such as that which connects a steering wheel’s rotating wiring to the steering column.

4 Conclusions

Both mechanisms developed in this project fulfilled the criteria of providing 3 DOF motion and appear to be distinct from identified robot head prior art. While the omni wheels driving a sphere design comprised an interesting mechanism, capable of delivering unlimited, holonomic motion from stationary actuators, it was not able to provide the necessary physical security or reliable control. It may, however, have applicability to a holonomic vehicle or a material transfer system. The final prototype, comprised differential gears and rotating frame, achieved the desired functional requirements and specifications in a compact, enclosed, scalable and easily mounted package. This new RA prototype was shipped to Japan for installation and field trial in a test vehicle to garner user feedback and looking forward, implementation of the RA on a production vehicle is now a more feasible option. This design is shared with other designers, in fields outside the automotive sector, who may be seeking alternative spherical actuation designs.

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