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# Cable-Driven Elastic Parallel Humanoid Head with Face Tracking for Autism Spectrum Disorder Interventions

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*Abstract*— **This paper presents the development of new prismatic actuation approach and its application in human-safe humanoid head design. To reduce actuator output impedance and mitigate unexpected external shock, the prismatic actuation method uses cables to drive a piston with preloaded spring. By leveraging the advantages of parallel manipulator and cable-driven mechanism, the developed neck has a parallel manipulator embodiment with two cable-driven limbs embedded with preloaded springs and one passive limb. The eye mechanism is adapted for low-cost webcam with succinct "ball-in-socket" structure. Based on human head anatomy and biomimetics, the neck has 3 degree of freedom (DOF) motion: pan, tilt and one decoupled roll while each eye has independent pan and synchronous tilt motion (3 DOF eyes). A Kalman filter based face tracking algorithm is implemented to interact with the human. This neck and eye structure is translatable to other human-safe humanoid robots. The robot's appearance reflects a non-threatening image of a penguin, which can be translated into a possible therapeutic intervention for children with Autism Spectrum Disorders.**

## I. INTRODUCTION

CREATING human-like robots is getting closer to reality with the increasing research on bionics.Most traditional robotic systems have been developed specifically for the purpose of working in a closed industrial environment where they are intentionally separated from human contact. It requires a fundamental change in the design of robotic systems to make them safe for direct interaction with people. Actuators and sensors continue to be major impediments to developing safe robots that resemble human beings. The goal is to develop robots that both will not harm people and be robust to human motion and reasonable external impacts so as not to not destroy the robot functionality. Generally, the development of humanoid robots in human environments is a multidisciplinary research area requiring meticulous consideration of safety and psychological issues including developmental appropriateness.

Autism Spectrum Disorders (ASDs) are a group of developmental disabilities characterized by atypical development in socialization, communication and behavior. The Center for Disease Control and Prevention estimates that an average of 1 in 110 children in the U.S. has ASD (www.cdc.gov). A child classified as autistic must show delays in the development of: social interaction, communication and behaviors. Social interaction includes non-verbal behaviors such as eye contact or gaze, facial expression, body posturing and gestures that regulate social interaction [1]. Children with ASD usually exhibit difficulty in responding appropriately to sensory messages.

In reflecting the new changes in the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) anticipated to come out in 2013, the robot will focus specifically on interacting with children with Autism Spectrum Disorder which encompasses all pervasive developmental disorders including Asperger's syndrome. While there is currently no specific cure for Autism, there are biomedical, therapeutic and educational treatment plans to remediate the delayed development and ameliorate behaviors. Social interventions use structured and planned curricula to teach social behaviors to children with ASD. However, social interventions to date are limited in the extent to which they address socially coordinated interaction. We propose the robot as an additional treatment in guiding early intervention for Autistic children; a humanoid robot would look at them, make social cues including facial expression and utterances, track eye contact and force the child to engage in social interaction. Since children with Autism often have trouble making friends and feel neglected, the non-judgmental robot may help them to associate feeling and emotions. A cartoon-like embodiment would be non-threatening and may help the children in learning to see beyond themselves. The robot would supplement traditional therapy and may provide a standardized assessment of the child's behavior and improve-

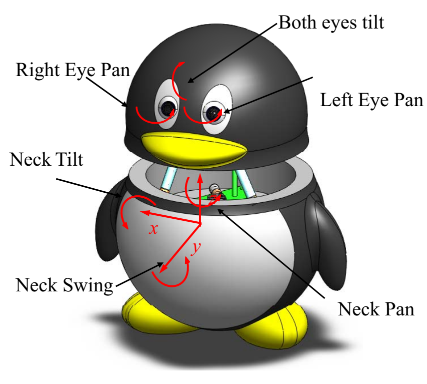


Fig. 1. A virtual prototype of the penguin robot with annotated degree of freedom.

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ment throughout the course of treatment. Because Autism in a spectrum disorder, there is no definitive medical test for identification; the robot could also help with diagnosis by quantitatively monitoring gaze and social cues.

Although electrical hardware and software safety mechanisms can provide some improvement, additional and potentially fundamental improvement relies on novel actuators and mechanical design, which have been in development in recent decades. The Series Elastic Actuator (SEA) is a simple but efficient technique developed by Pratt and Williamson [2]. A linear elastic spring is used to connect the motor while the force or torque of the actuator can be easily computed using Hooke's law. The researchers from Massachusetts Institute of Technology have developed a diverse array of humanoid robots to perform daily life manipulation in human environments based on this actuation technique [3]–[5]. RoboKnee [6] and IHMC Mobility Assist Exoskeleton by Kwa et al. [7] are examples of exoskeleton systems using very similar SEAs. The distributed macro-mini actuation is another novel actuation method that aims to redistribute the major source of actuation effort from the distal joints to manipulator base. The effective inertia and weight of the overall manipulator are reduced dramatically [8].

More specifically, the humanoid robot design has strived to address detailed mechatronic issues in many respects. Kozima *et al* [9] designed a 4 DOF interactive robot Keepon to interact with children with autism. This simple and adorable robot gave the children a playful and joyful mood and helped them to transfer the interpersonal communication learnt with Keepon to triadic play with adults or other children. Beira *et al* [10] analyzed the human neck and eye anatomy and compared spring neck, parallel neck and the final serial neck. Because the actuators in that 3 UPS (U represents universal joint, P represents prismatic joint and S represents spherical joint) parallel manipulator are coupled with the limbs, the limited space make it very difficult to avoid the interference between the various parts. The final solution is a serial manipulator made of three orthogonal DC motors with overload clutch system. The human safety issue is not well considered. [11] presented the design experiences of mechatronic components of the upper body of the humanoid robot ARMAR III.

To bridge the gap between parallel manipulator and cable-driven mechanism, this paper presents the development of human-friendly humanoid head with compliant neck and actuated eye mechanisms. By leveraging the advantages of both mechanisms, the developed neck has a parallel manipulator embodiment with two cable-driven actuated limbs embedded with preloaded springs and one passive limb. The actuated eye mechanism allows stereo vision using a pair of low-cost webcams. Based on human head anatomy and biomimetics, the neck has 3 DOF motion: pan, tilt and one decoupled roll while each eye has independent pan and synchronous tilt motion (3 DOF eyes). Fig. 1 is a virtual prototype of the penguin robot with annotated degree of freedom. A Kalman filter based face tracking algorithm is implemented to track face motion and achieve simple human robot interaction. This neck and eye structure is translatable to other human-safe humanoid robots. The robot appearance is a cartoon penguin which makes it ideal for child interaction. Our ultimate goal is to develop a cost-effective human-friendly robot to permit ease of evaluation of human-robot interaction.

This paper is organized as follows: Section II describes the overall system architecture with an emphasis on the parallel manipulator neck mechanism and a detailed description about the elastic prismatic limb. Section III describes a compact "ball-in-socket" spherical manipulator to simulate eye motion and drive a pair of generic webcams. Finally, a discussion of the system is presented in Section V.

## II. Neck Mechanism

The neck model has been thoroughly investigated in biomechanics community for the analysis of head injuries and the standard model includes 4 DOF [12]. In this design, the upper neck flexion/extension was ignored for simplicity while it could be set up by adding one more prismatic joint.

As a generic manipulator to support the head's mechanical and electrical components, the neck mechanism should be compact and self-contained. Even though parallel mechanisms have many desirable characteristics such as high rigidity, high load capacity and simple closed form inverse kinematics, many researchers have demonstrated difficulty in implementation due to space limitations [10]. The mechanism presented here aims to address the problem by using a passive joint and two active elastic prismatic joints. Fig. 2 shows a CAD model of the first iteration of this parallel neck.

### *A. Parallel Neck Mechanism*

The degrees of freedom of motion of the neck could be accomplished with a 3 DOF parallel mechanism. Merlet [13] has classified 9 variants of this kind of parallel mechanisms in terms of motion type and geometrical architecture. 3 UPS seems to be an ideal solution for this application, but this mechanism suffers from both limited range of motion and geometric singularities. To resolve this, we proposed a parallel mechanism with two cable-driven actuated UPS limbs embedded with preloaded springs and one passive limb. This structure provides 2 DOF pan and tilt motion while the roll motion is accomplished through a decoupled

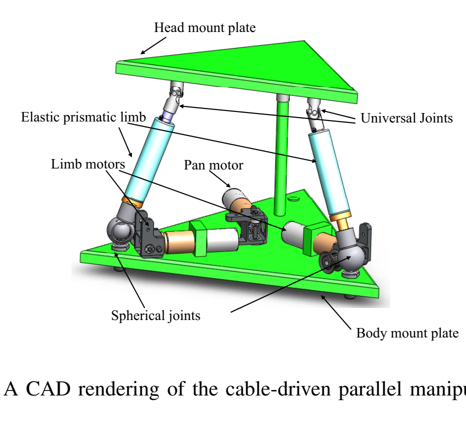

Fig. 2. A CAD rendering of the cable-driven parallel manipulator head.

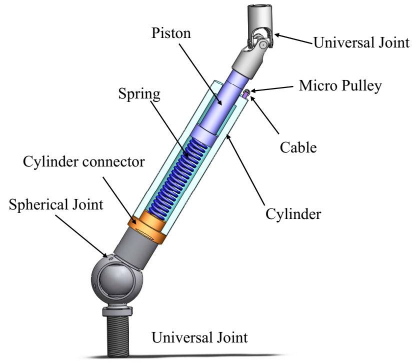


Fig. 3. A CAD rendering of a cable-driven elastic limb.

rotary motor. This mechanism overcomes the singularity problems, decouples and improves the neck rotation range of motion, and makes the system compact and easy to control. The inverse kinematics is similar to 3UPS manipulators and the interested readers can refer to [14] for more details.

### B. Cable Driven Elastic Limb

Each active limb has a universal-prismatic-spherical joint connection. Fig. 3 shows a CAD rendering of a cable-driven elastic limb. One piston is inserted into a hollow cylinder and pushed against a preloaded spring. The cable (not shown) running from the motorized pulley connects to the base of the inner piston. When the motor winds the cable, the piston extends and when the motor releases the cable, the piston retracts. The spring provides the retraction force while a spring-loaded cable tensioner allows for compliance in the retraction direction and to take up excess slack if an external force extends the piston. Since all motors are fixed on the base, the inertia of the moving part is small and would mitigate the limb interference issue.

## III. Eye Driver Mechanism

The eye mechanism design provides a simple and compact motion driver to accurately control the eye ball orientations in a decoupled manner. Each eye contains a spherical webcam (Logitech, Switzerland) which provides stereo vision and the ability to both tracks faces and provides facial cues. The proposed mechanism is bio-inspired with a "ball-in-socket" structure to provide realistic eye motions. Each eye has $90^o$ pan and $90^o$ tilt motion capability. The current design couples the tilt of both eyes to constrain 1 DOF motion which would guarantee synchronous tilt motion as shown in Fig. 4. The camera itself has a horizontal $50^o$ degrees and vertical $37.5^o$ degrees view angle. The mechanism combined with the cameras provide for human-like speed and range of motion providing a $90^o$ motion in under $0.18s$.

The pan-tilt mechanism for the eyes has some subtle but important advances over the prior art [10]. The first improvement was the use of low cost servo motors (Sub-Micro Servo, HobbyPartz, CA) with $7g$ Weight, $1.6kg/cm$ torque and $0.12sec/60^o$ speed and $\pm1^o$ positioning accuracy. The speed is comparative with human eye ($166^o/sec$ to $850^o/sec$) [10]. These allow a reduction in overall cost without compromising functionality. These motors are easier

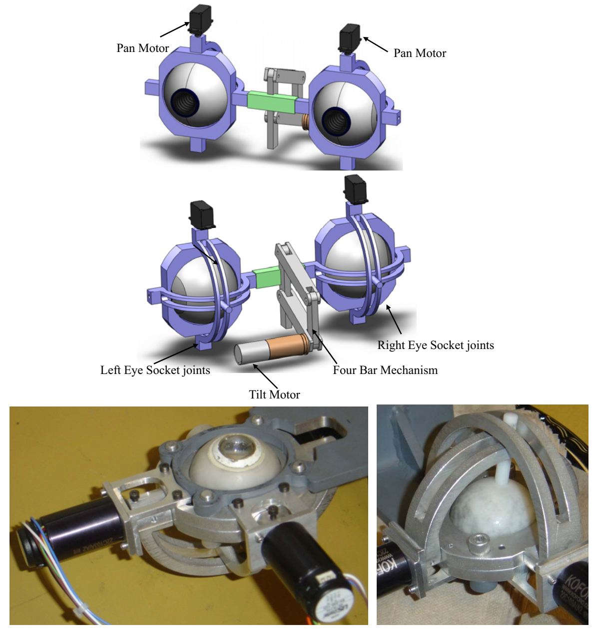


Fig. 4. Front and rear views of "ball-in-socket" structure of eye mechanism that will contain webcams and a prototype realization of the eye motion simulator.

to control and reduce processing overhead and the need for IO down to just one digital line per motor (as opposed to requiring encoders, amplifiers, and external feedback control). As a tool for research, this system is inexpensive to acquire and straightforward to assemble. Another advantage of the pan-tilt mechanism is the guide pin at the back of the assembly serves to guide the cables out of the mechanism without getting pinched which reduces wear on the cable minimizing the need for servicing the eye mechanism.

## IV. Kalman Filter based Face Tracking

### A. Extended Kalman Filter

Estimating face postures is essentially a nonlinear stochastic estimation problem. The extended Kalman filter (EKF) is the first-order Taylor expansion of the nonlinear state space functions and has been successfully implemented in many areas. The face images are transformed to polar coordinates to drive the neck mechanism. The 6 dimensional state vector includes the pan and tilt angle in camera coordinate and their corresponding velocities and acclamations. The nonlinear estimation can be expressed as:

State Transition Model

$$x_k = f(x_{k-1}, u_{k-1}) + w_{k-1} \quad (1)$$

Observation Model

$$z_k = h(x_{k-1}) + v_k \quad (2)$$

where $w_k$ and $v_k$ are process and observation zero mean Gaussian noise with covariance matrices $Q_k$ and $R_k$ respectively. The EKF linearizes about the current mean and covariance and recursively estimate the states while minimize a posteriori estimation error covariance $P_{k|k}$ with the following structure

Prediction

$$\hat{x}_{k|k-1} = f(\hat{x}_{k|k-1}, u_{k|k-1}) \tag{3}$$

$$P_{k|k-1} = F_{k-1} P_{k-1|k-1} F_{k-1}^T + Q_{k-1} \tag{4}$$

Update

$$\tilde{y}_k = z_k - h(\hat{x}_{k|k-1}) \tag{5}$$

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \tag{6}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \tag{7}$$

$$\hat{P}_{k|k} = (I - K_k H_k) P_{k|k-1} \tag{8}$$

where $P$ is the estimation error covariance, $K_k$ is the Kalman gain, $F$ and $H$ are Jacobian defined as

$$F_{k-1} = \frac{\partial f}{\partial x}|_{\hat{x}_{k-1}|k-1, u_{k-1}} \tag{9}$$

$$H_k = \frac{\partial h}{\partial x}|\ \hat{x}_{k-1|k} \tag{10}$$

### B. Implementation

Gathering the list of faces was simplified by using Python bindings for the OpenCV library [15] at $30Hz$. An image object was passed to the program and a list of $x - y$ coordinates were returned. Each element of the list is the $x - y - z$ position of the face as determined by OpenCV. The $z$ position is always zero since in the current physical prototype, only one camera with no reference of the size of the face is used.

Fig.5 illustrates the overlay of the measured face position from OpenCV and filtered results. The filter applied to the data is a position-velocity-acceleration Kalman filter. Issues that must be addressed for the data output from the OpenCV face identifier include: 1) it does not make the distinction between one face and another, 2) it will not have a reliable output if there is more than one face in the image, and 3) it can have significant frame to frame variations in calculated location of the face. The Kalman filter used makes the assumption that a face is unlikely to move in the frame more than a few degrees from the previous measured position, which has been validated in preliminary experiments with the camera. We can use the Kalman predictions to distinguish which face from the list provided by OpenCV is the face that was previously being tracked. Therefore, a stream of facial images from the camera can be smoothed to the path seen in Fig. 5 which illustrates the tracking sequences with superimposed green circles showing the position measurement and black square showing the estimated position.

## V. Discussion

This paper described a cable-driven elastic parallel manipulator neck and a "ball-in-socket" eye mechanism for humanoid robot design. A Kalman filter is implemented to track human face motion. Future work includes construction of the system design and generating human-like motion and expression integrating elements of a previous work on robot expressions. Motion of the appendages and vocal cues may also be implemented in future iterations. Head sensing using force sensors [16], [17] would increase the robot perception and interaction capability. With the completed system in place, we intend to use the robot as a research tool to study how humans interact with robots and how humans interact with other humans. We plan on using the robot as both an assessment and interventional tool for interacting with children with Autism Spectrum Disorder.

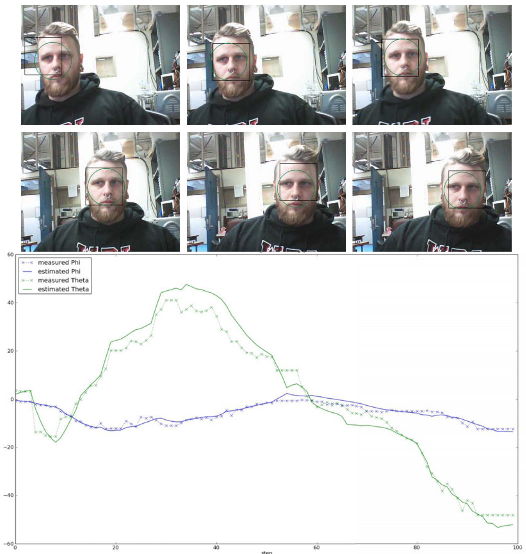


Fig. 5. Tracking sequences with superimposed green circles showing the position measurement and black square showing the estimated position (top). Measurement and estimated pan and tilt values (bottom).

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