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Edubot: a Reconfigurable Kit for Control Education – Part I: Mechanical Design

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Abstract

This paper describes the mechanical design of a reconfigurable educational robotic kit, named the Edubot. This kit can be easily assembled to perform a wide range of both linear and non-linear control system experiments. The modular design is described and a subset of the possible configurations shown. Two prototyped designs are detailed and critiqued. A Pendubot and an Acrobot are used as case studies to demonstrate the kit.

1. Introduction

Rensselaer Polytechnic Institute (RPI) has always been known for supplementing lectures with experimental laboratory exercises in the classroom, but has recently been taking the hands on approach for learning to a new extreme. The Edubot was developed at the Center for Automation Technologies at RPI to provide students and researchers alike with an inexpensive mechatronic kit to be used in classrooms and research laboratories. The kit consists of an assortment of well characterized building blocks (modules) that can be quickly assembled into a wide range of experimental testbeds. For example, a single Edubot kit can be assembled as a servo positioner to demonstrate PID control, an under-actuated double-pendulum (Pendubot [1] and Acrobot [2]) to demonstrate non-linear control, or a flexible link positioner to demonstrate non-minimum phase control. Since all of the modules for the kit are well characterized in terms of mass properties and friction, additional time is saved because experimental parameter identification exercises become an optional activity.

2. Design Objectives

Before building the Edubot, physical constraints and philosophical objectives were defined to emphasize effectiveness in the classroom environment and utility in the research environment.

Physical Constraints

The Edubot should be small in size, so that a student can build the entire experiment on a desktop. Envisioning that a classroom might have several small groups of students, with each group sharing their own Edubot kit, a low production cost is also important. Since the Edubot would be subject to untested control schemes, the Edubot must be rugged enough to withstand unstable controllers. To demonstrate the power of mathematical modeling and simulations, the Edubot should "behave" consistently with common modeling assumptions and simplifications. Thus, the Edubot should be repeatable, have low backlash and predictable friction characteristics.

Philosophical Objectives

The primary objective was to create a kit that allowed for assembling the greatest range of experiments with the minimum number of components. From class to class, the students may want to perform different experiments with the same Edubot kit, so the kit should be quick and easy to reconfigure. The basic configurations should be inherently easy enough to control so that a novice control system student can successfully design a simple control scheme that works on real hardware. The kit should not only be reconfigurable, but also be ultimately flexible so that more challenging and novel configurations can be assembled for more advanced controller design. The hardware should be fully characterized so that a full non-linear model can be readily calculated without requiring parameter identification exercises. Finally, as with all robotic systems, user safety should be of high concern.

3. Module Description

It was decided that a modular technique allowed for great flexibility in constructing a wide range of experiments. The basic modules come in the form of joints and links, with all modules sharing a common bolt pattern to be universally interchangeable with each other.

The Joint modules come in two forms, motorized joints and free spinning (un-motorized) joints. All Joint modules have an optical encoder to provide for position information. The Link modules come in a range of shapes, weights, lengths, and materials. The basic Link modules include a short carbon fiber link, a long aluminum link, a spring steel flexible link, a gyro wheel, and a dummy mass.

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Configuration	Motorized Joint	Free Joint	Short Link	Long Link	Flexible Link	Gyro Wheel	Dummy Mass
Motor Velocity Control	*					*	
Servo Positioner	*		*				*
Servo Positioner with gravity disturbance	*		*				*
Servo Positioner with Flexible Link	*				*		*
Rotary Inverted Pendulum	*	*	*	*			
Pendubot	*	*	*	*			
Pendubot with Flexible Link	*	*	*		*		
Acrobot	*	*	*	*			
Gyro Positioner	*	*	*			*	
Gyro Positioner with gravity disturbance	*	*	*			*	
Two Link Robot	**	**					*
Double Pendubot	*	**	**	*			
Teleoperated Servo Positioner	**	**					*
Teleoperated Two Link Robot	****	****					**

Figure 1 Table of Configurations

The mass properties for each module were determined through precise CAD solid modeling. Solid modeling CAD packages allow density information to be associated with each part of a module (gear, shaft, bearing, etc.) and can calculate the mass, the location of the center of mass, and the inertia tensor for that module. For the single degree-of-freedom motorized joint, a lumped parameter rotational inertia (rotor, shaft, and gears), a lumped parameter viscous friction and a coulomb friction term were determined by a least squares fit to experimental data.

The power and usefulness of using fully characterized modules is threefold. First, the close correlation between calculation and simulation with actual real world performance is emphasized to the student. Second, time is saved because parameter identification exercises are not required. Third, by knowing almost exact mass properties, the accuracy of parameter identification techniques can be quantified.

4. Configuration Description

One Edubot kit contains a motorized joint, free spinning joint, short link, long link, flexible link, gyro wheel, two link mounts, and a dummy mass. A select subset of the configurations that can be assembled with the Edubot kit are shown in Figure1, "Table of Configurations".

The Pendubot configuration, Gyro Positioner configuration, and Acrobot configuration are shown in Figure 2, "Example Configurations". Notice that the Pendubot configuration grounds the motorized joint and locates the free joint on the outboard end of the short link, while the Gyro Positioner configuration grounds the free joint and locates the motorized joint on the outboard end of the short link.

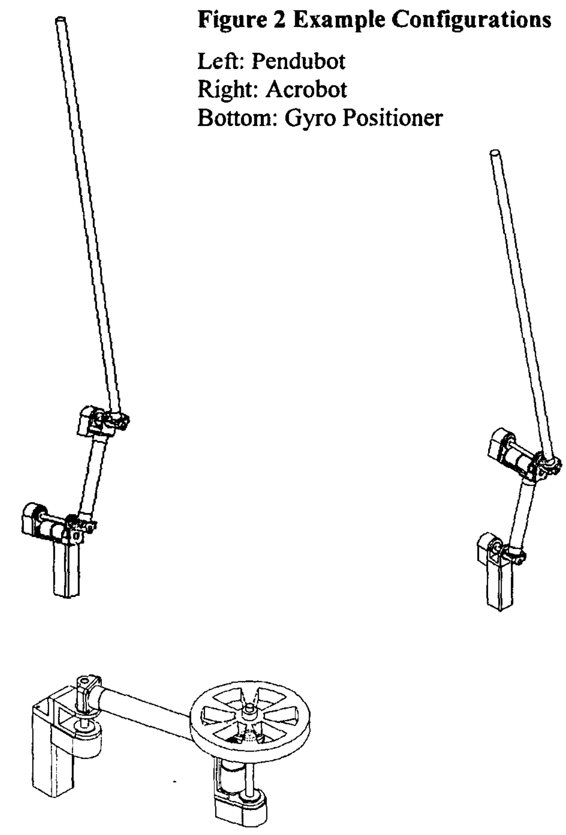

Figure 2 Example Configurations

Left: Pendubot
Right: Acrobot
Bottom: Gyro Positioner

5. Design Iteration I

The motivation in designing the first prototype kit was to answer the question, "How small and compact can the kit be made while maintaining acceptable performance and ease of controllability?" By using small motors and low mass links, the kit would not only fit on a desk, but would also be safe. From a performance standpoint, since the motorized joint is sometimes mounted on the outboard end of a link, such as in the Acrobot or gyro positioner, it is very important that the mass of the motorized joint and integral motor be minimized. A 2 watt MicroMo® coreless motor was selected to power the motorized joint. The coreless motors produced by MicroMo® (and other manufactures) do not contain a ferrous core in the rotor, but instead use a bird-nest-like weave of copper wire to form the rotor. The very small rotational inertia of the rotor combined with powerful rare earth magnets and integral planetary gear reduction result in a quick and relatively powerful gearmotor in a very small and light weight package. The motor was oriented perpendicular to the motorized joint output shaft as shown in Figure 3, "Motorized Joint for Iteration I". When the motor is oriented in this manner, the total inertia of the short link/motorized joint is less then that when orienting the motor parallel to the motorized joint output shaft. Bevel gears were used to transfer power from the gearmotor output shaft to the Motorized joint output shaft. Backlash is inherent in the planetary gearhead, so a bevel gear ratio of 3:1 was chosen to lessen the backlash at the Motorized Joint output shaft. As an example of this effect, imagine that the gearhead has 1 degree of backlash. If the bevel gear mesh is assumed to be free of backlash, then the 1degree of backlash at the gearhead results in only 1/3 degree of backlash at the motorized joint output shaft. The output shaft of the gearmotor was not strong enough to handle the tangential loads induced by the bevel gears, so a stronger shaft supported by two miniature ball bearings was used to mount the bevel gear. When coupling two co-axial and fully constrained shafts, such as the motor output shaft to the support shaft, a common problem that occurs is excessive loads due to angular and axial misalignment. A solution to this problem is to connect the two shafts with a flexible coupling which is flexible to bending moments and shear loads, but rigid to torsional loads. The encoders were attached to the Motorized Joint output shaft as opposed to the motor itself to reduce uncertainty in joint position due to backlash. The output shaft for the motorized joint was sized at 3/16 inch and was supported by two miniature ball bearings. Duncan 1024 count encoders were selected primarily because of their small diameter and light weight. As one of the more expensive parts of the kit, the encoders were designed to be easily detached from the joint and attached to another joint. Rubber O-rings were used to couple the encoder to the Motorized Joint output shaft to both absorb shaft misalignment and provide for quick disconnect for the encoders. Set screws were used thoughout to attach gears to shafts, the flexible coupling, and the link to the Motorized Joint output shaft. A drawing showing how the motor is nestled inside the hollow short link of the motorized joint is shown in figure 4, "Motor Orientation for Iteration I".

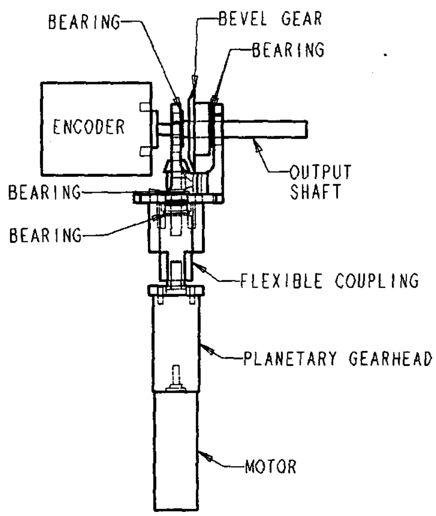

Figure 3 Motorized Joint for Iteration I

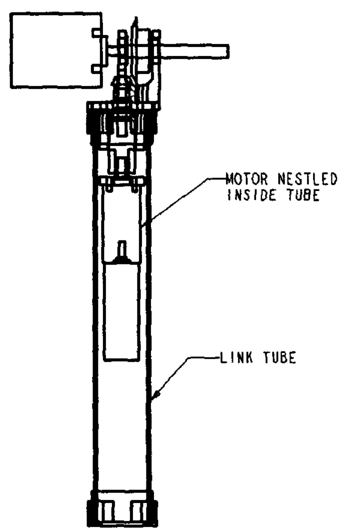

Figure 4 Motor Orientation for Iteration I

Pro-Engineer® Solid Modeling CAD software was used to design and model all parts of the kit. In this manner, the parts can be virtually fit together to check for clearances and interferences before any metal is cut. Additionally, material properties can be assigned to all of the parts in an assembly. Pro-Engineer® can then calculate the center of gravity and full inertia properties for assemblies with very complex shapes and parts made of many different materials. A CNC (computer numerically controlled) milling machine was then used to machine the parts directly from the CAD part files.

6. Critique of Iteration I

The first model was used successfully to demonstrate servo positioning and balancing the Pendubot configuration, but showed some characteristics that made it unsuitable for educational use. The linear full state feedback controller designed using the parameters from the CAD model did not work. However, by using parameters determined with a multi-parameter identification scheme [3], a linear full state controller was able to balance the Pendubot with considerable hand tweaking of the gains. Two complete first generation prototypes systems were built, but because of variations in the machining and the critical mesh of the bevel gears, each system had its own personality and required slightly different controller gains to balance the Pendubot. These characteristics make the design unsuitable for demonstrating the correlation between a simulation and the behavior of a physical system in the classroom.

The multi-stage grease lubricated planetary reduction resulted in a large frictional component and significant backlash. The bevel gears by nature required extremely tight machining tolerances and careful shimming to achieve a good mesh. Although the output shaft and miniature bearings showed no signs of being over stressed, the play in the miniature bearings and close spacing of the bearings allowed for noticeable out of plane motion of the first link. The very small set screws had a tendency to loosen and could not be tightened adequately without stripping the miniscule Allen wrench. The rubber O-ring interface between the encoder and the motorized joint output shaft worked when the encoder was well aligned, but could walk if the encoder was misaligned. Encoder misalignment did occur because of the design of the quick-change encoder mounts. During attempts at multi parameter identification for the Pendubot and Acrobot configurations, the motor speed saturated for large control inputs. This non-linearity made multi-parameter identification very difficult. Therefore, identification has to be performed with limits on the torque inputs for the sinusoidal stimulation. Expectedly, the continuous wires connected to the outbound motor and encoder prevented the joints from continuous rotation and proved to be a weak point if the joint rotated further than one revolution.

7. Design Iteration II

Having learned from the first prototype, the emphasis on the second iteration was to focus on making the kit more "Ideal", in other words easier to model, while fixing some of the usability and reliability problems identified in the first generation prototype.

To address the backlash and friction problems, a more powerful MicroMo® motor was selected along with a planetary gear reduction with a smaller gear reduction. The larger gearmotor produces approximately the same torque as the smaller gearmotor, but can achieve higher speeds to help prevent speed saturation. The gearmotor still had backlash, so an external spur gear reduction was used to reduce the backlash. Since this motor had a stronger output shaft, the pinion gear could be mounted directly on the gearmotor output shaft, thereby eliminating the flexible coupling, two bearings, and the support shaft from the motorized joint. Using the spur gear configuration, alignment is not as critical. Using spur gears however, the motor must be mounted parallel to the axis of the motorized joint output shaft. This has a detrimental effect on the moment of inertia of the composite short link-motorized joint inertia properties and sacrifices compactness. To help eliminate out of plane motion, larger ball bearings with tighter tolerances were mounted further apart and a ¼ inch motorized joint output shaft was used. The Encoders were replaced with Hewlett Packard 1024 count encoders and permanently attached to the joints. These encoders do not have bearings to support the disk, but rely on the user to supply a shaft to mount the encoder disk. This means that the encoders must be carefully aligned with the shaft. This eliminates the need for the flexible coupling between the encoder and the motorized joint output shaft, but requires tighter tolerances for assembly. Pins were used to attach the link to the motorized joint output shaft instead of set screws, which still allow for quick and easy assembly and dis-assembly but are not prone to loosening. See Figure 5, "Motorized Joint for Iteration II" for diagram of the Joint layout. As in the Iteration I design, mass properties were determined directly from the CAD model.

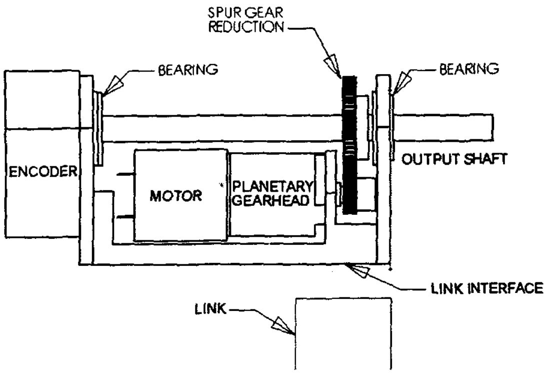

Figure 5 Motorized Joint for Iteration II

8. Critique of Iteration II (Pendubot and Acrobot Examples)

After building the second generation prototype kit, the first configuration tested was the Pendubot. A linear full state feedback controller was designed based on the mass properties generated from the CAD program and the identified parameters on the motorized joint. Velocity states were estimated with a full state observer. The controller was implemented on an ARCS real time control board using the C programming language. The ARCS board is a motion control board based on a Texas Instruments DSP chip and provides an easy to use interface.

After debugging the code, the Pendubot was found to balance very nicely. Various feedback pole locations were tested, but it was found that placing the feedback poles at (-10, -8 –4+.1i, -4-.1i) resulted in stable performance with good disturbance rejection. Placing the observer poles about 5 times further to the left of the feedback poles resulted in a smooth estimation of the velocity states. No hand tweaking of the gains was required to get good performance. A picture of the Pendubot balancing is shown in Figure 6, "Pendubot Balancing".

The second configuration tested was the Acrobot configuration. Using the feedback poles that worked well for the Pendubot, the Acrobot balanced on the very first try! Again, no hand tweaking of the feedback gains was required. A picture of the Acrobot balancing is shown in Figure 7, "Acrobot Balancing".

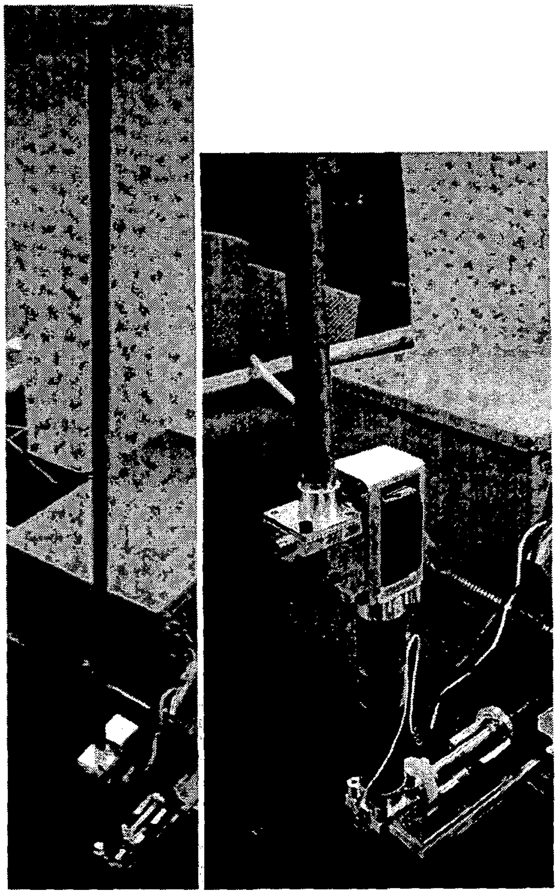

Figure 6 Pendubot Balancing

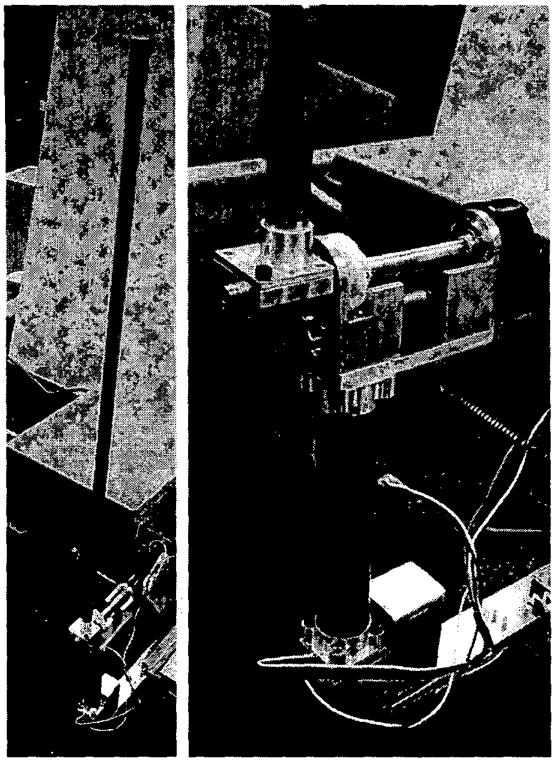

Figure 7 Acrobot Balancing

9. Conclusions

Prototypes for an inexpensive and reconfigurable mechatronic kit, called the Edubot, were designed and built to satisfy the needs of professors and researchers at RPI. Two iterations in the design were required to achieve satisfactory fulfillment of the design objectives. Although the first generation prototype had certain desirable features, it was not repeatable or easily modeled. The second generation prototype performed as required, but sacrificed some of the desirable features found in the first prototype. A third Generation kit with an integral slipring to allow the joints to spin indefinitely without wrapping the encoder wires is now being constructed and evaluated for performance. Additionally force feedback and telepresence experiments involving two Edubot kits are being conducted.

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