Novel Assistive Device for Teaching Crawling Skills to Infants

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Abstract

Crawling is a fundamental skill linked to development far beyond simple mobility. Infants who have cerebral palsy and similar conditions learn to crawl late, if at all; pushing back other elements of their development. This paper describes the development of a robot (the Self-Initiated Prone Progression Crawler v3, or SIPPC3) that assists infants in learning to crawl. When an infant is placed onboard, the robot senses contact forces generated by the limbs interacting with the ground. The robot then moves or raises the infant's trunk accordingly. The robot responses are adjustable such that even infants lacking the muscle strength to crawl can initiate movement. The novel idea that this paper presents is the use of a force augmenting motion mechanism to help infants learn how to crawl.

1 Introduction

Cerebral Palsy (CP) is a common physically disabling condition for children in the United States. Estimates of prevalence vary between 3 to 10 out of 1,000 children depending on gestational age at birth [1]. A non-progressive disorder of the nervous system, CP is characterized by atypical patterns of movement associated with inadequate muscle force production, incoordination, poor temporal and spatial organization of muscle and joints, and postural instability. Sensory deficits in proprioception, tactile discrimination or vision also interfere with a child's ability to select appropriate movement strategies [2, 3]. Although CP is non-progressive, there is a gradual reduction in spontaneous movements during the first year of life by infants who are later diagnosed with CP [2].

Of the numerous complications often experienced by children and adults with CP, the most disabling is mobility. The problems with mobility do not only disrupt functional independence across the lifespan [4], but are also associated with the high cost of CP. Estimates of lifetime costs for all individuals with CP who were born in 2000, in the US, totaled $11.5 billion [5].

The earliest, and, in some cases, the only form of functional mobility available to typically developing children during the first year of life is prone locomotion, such as crawling and creeping. However, these important milestones are extremely compromised in children with severe CP. The literature describes prone locomotion as a complex skill, as it requires integration of at least three key components of mobility that infants with CP often lack: progression, stability, and adaptation [6]. For infants, locomotion is a gateway to self-determination, autonomy, and learning; the basis for early functional independence and exploration, and, therefore, important in its own right. A large body of knowledge supports the inter-connection between prone locomotion and other domains of infant development that are critical for learning and education [7, 8, 9]. The emergence of prone locomotion in infants also coincides with a period of highly active synaptic formation in the brain [10]. This period is critical to the integration of other functions important for cognition and social interaction [8].

Fig. 1: *SIPPC3 in action*

Therefore, for children with CP, lack of locomotion during infancy may not only negatively affect later motor-related functions, but also attainment of other skills necessary for successful social inclusion. The lack of adequate muscle force production in infants with CP plays a big role in hindering mobility. If they can be provided with force assistance such that enables mobility, then they can have a better chance to achieve relevant developmental milestones at a pace similar to that of typically developing infants.

We have created a robotic system, the SIPPC3 (see Figure 1), to help children with CP develop prone locomotion skills (crawling). The system consists of the robot and an operator's laptop for control and datalogging. A subject is placed in the SIPPC3 in a prone position. The robot supports the subject at a pre-set height or moves up the torso based on the upwards forces exerted by the subject. Forces exerted in the horizontal plane are used to generate motions of the robot in the appropriate direction.

Section 2 describes requirements, constraints, and related work. Sections 3 through 5 detail the SIPPC3 robot's mechanical and electrical systems, and control laws. Section 6 describes some preliminary testing of the robot. Finally, conclusions and future work are discussed in Section 7.

2 Motivating Factors for the SIPPC3 Design

2.1 Previous Approaches

There have been a number of robotic approaches to assist infants with Cerebral Palsy to obtain mobility. Some researchers have created robots that the infant can ride, [11], which, while potentially giving the child some sense of independent mobility, does not develop any motor skills or have any of the other benefits of physical activity. Schoepflin, [12], working with somewhat older children (3-4 years) developed an assistive device more similar in action to a robotic pedal cart. Children in a sitting position could activate and control the cart (a seat mounted on a Pioneer robot platform) by using a pedaling-like motion. Kolobe, [13] describes some earlier, related, work in prone locomotion. This earlier SIPPC could amplify some of the movements initiated by the child, but the fixed height put children in an advanced crawling position, regardless of their age or crawling developmental stage. This was the SIPPC2. An earlier version of this was the SIPPC1 which was a passive platform with no assistance in movement.

2.2 Requirements and Constraints

Children learn to crawl in stages. They start in a prone position close to or on the ground. As they develop, they lift more of their body off the ground and eventually move to an alternating pattern on their hands and knees. Orientation of the head is important, especially during the transition in development from lying flat on the ground to the point where the head is lifted above the shoulders [14]. Infants are very interested in their surroundings and will grab at near objects that are within view. Children with or at risk of CP may have reduced muscle strength, If they are interested in objects in their surroundings, they may not be able to generate the force required to mobilize the body during crawling.

Our robotic assistant needs to allow children to be in the prone position, and be as close to the ground as possible while still providing adequate support for breathing. The robot should be able to assist the child in weight bearing. A crawling infant may use just their arms, legs or coordinated action amongst all four of their limbs when moving, and so the robot should be able to move the child in any direction and rotate around any point. The robot should also be able to constrain those movements and points of rotation in order to encourage more productive crawling behavior. The robot also needs to be able to handle children of different sizes and weights. Finally the robot needs to give an infant a clear view of where he/she is headed, and to give access to objects (e.g., toys) in front of the infant, so that he/she can plan and execute goal-driven movements [15].

3 SIPPC3 Crawler Mechanical Design

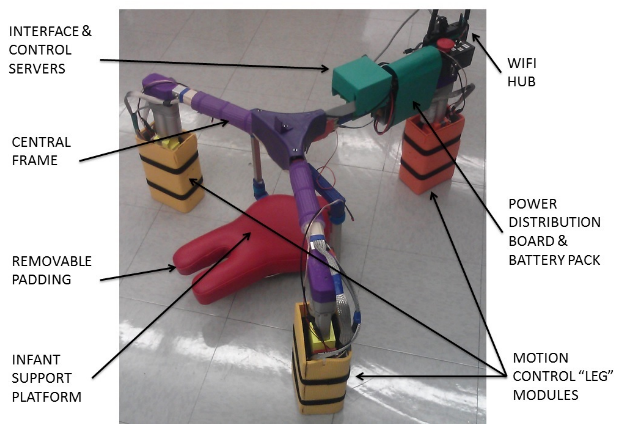

Fig. 2: *Overview of the mechanical system.*

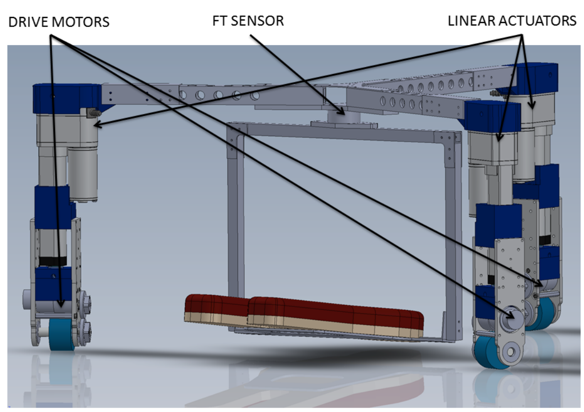

Fig. 3: *CAD model of SIPPC3 with leg detail exposed.*

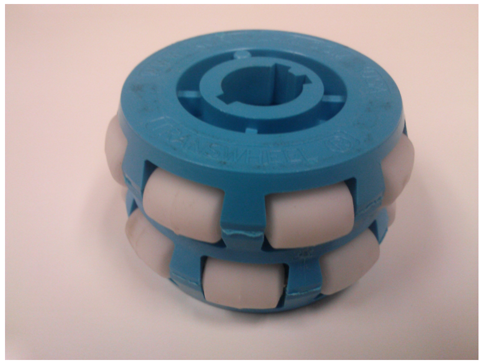

Fig. 4: *Omni-wheel drive for holonomic motion.*

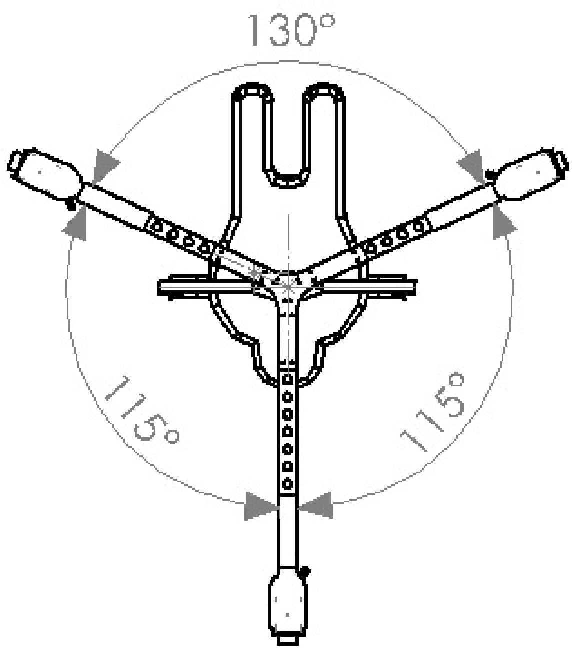

Fig. 5: *Relative angles between the Y-frame.*

The key requirements for the mechanical design of the robot are support for infant movement in any direction along the floor and in the vertical direction. Accordingly, we have developed a system with 4 DOF motion, of which 3DOF along the floor are achieved by using omni-wheels (see Figure 4). All this needs to be done using a minimum possible number of wheels and supporting structure while giving an infant a wide view of the surroundings.

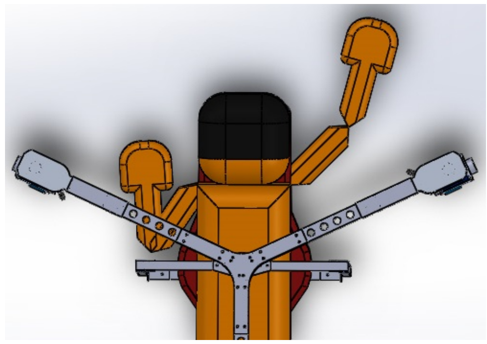

Fig. 6: *Overhead view showing typical arm and head positioning.*

The mechanical structure of the robot is designed around an infant support platform (Figure 2). This platform is mounted to a Y-shaped central frame (see Figures 2, 5) with three motion control modules or "legs". We have selected a Y-shape because it allows for 3 legs which is the smallest number of legs we can use to support the infant. The Y-shape is helpful since having the front two legs spread to the sides gives the infant a reasonably sized an unobstructed view. The infant support platform is a frame with a padded base on which an infant can lie down in a prone position. The padded base is tilted up by 7° to assist infant breathing. A 6 DOF FT sensor with integrated electronics [16][17] is the mechanical interface between the infant support platform and the central frame (see Figure 3). This ensures that all forces exerted by the infant below will be transferred to the robot through the FT sensor.

The legs are mounted at the ends of the central frame. Together, the legs provide 4 DOF motion for the infant support platform: one for raising the platform off the floor, and three for moving it in x, y, and yaw around the z-axis (see Figure 5). Each of the legs contains a linear actuator (see Figure 3) that can extend to raise the infant support platform. Built-in potentiometers in each actuator provide position feedback. The actuators are not backdrivable so they do not consume power to maintain a given height, nor will they suddenly move if there is an unexpected power loss.

For motion across the floor, each leg has a 131:1 geared DC motor driving an omni-wheel (see Figure 4). Omni-wheels were used to allow variability in movement patterns. Built-in quadrature encoders provide rotation feedback of the wheels. Each omni-wheel is oriented such that the axis of rotation passes through the center of the robot. This forms a holonomic drive configuration. Our configuration is different from the typical three-wheel holonomic configuration where all the wheels are positioned 120° apart and at the same radial distance from the center. Instead, the angle between the two front wheels has been widened to 130° (see Figure 5). The central frame has the front wheels closer to the center than the rear wheel. The wider angle is to allow the infant to have a wider unobstructed field view. The front wheels are closer to the center, making the robot smaller and more maneuverable in homes while maintaining adequate workspace for the subject's arms (Figure 6).

To protect the baby from the mechanical and electrical parts, the “legs” have been surrounded by aluminum sheet metal enclosures. The sheet metal (as are most of the hard surfaces in the SIPPC3) are covered by soft, brightly colored padding (see Figure 2).

4 Control Electronics

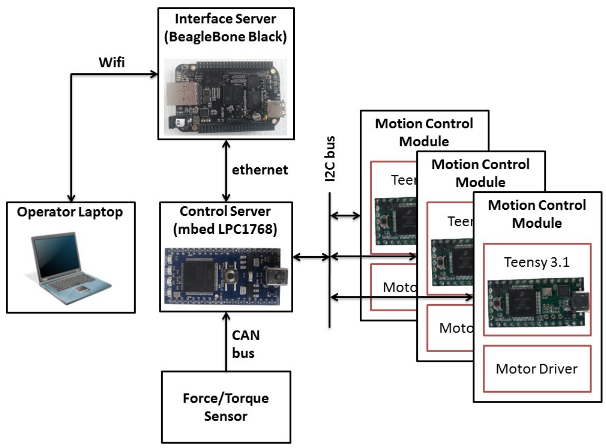

Fig. 7: *Overview of the control electronics.*

The electronic subsystems comprise an onboard WiFi hub, an Interface Server, a Control Server, Motion Control “leg” Modules, and the FT sensor (see Figure 7). These communicate over three different physical layers: ethernet (using TCP-IP), I2C, and Controller Area Network (CAN[18]). Ethernet connects the Interface Server, the Control Server to the WiFi hub. An I2C bus links the three Motion Control Modules and Control Server. CAN bus connects the Control Server to the FT sensor.

The Interface Server is an ARM® Cortex-A8 processor (BeagleBone Black[19]) running a stripped down version of the Ubuntu operating system. The Control Server is an ARM® Cortex™-M3 micro-controller (mbed LPC1768[20]). Each Motion Control Module is made up of a Cortex™-M4 micro-controller (Teensy 3.1[21]), a 2-channel motor driver, a linear actuator, and DC motor.

The Interface Server receives commands from the operator’s laptop over WiFi. It transmits back system health, sensor, and odometry data. The Interface Server generates synchronization signals for external recording devices.

The Control Server is central to the functioning of the robot. It receives commands from the Interface Server and relays back system health and odometry data.

It receives the FT data from the 6 DOF FT sensor and computes wheel velocity and actuator height set points for the three legs. These set points are then transmitted to the Motion Control Modules. Each Motion Control Module runs a feedback control loop through the motor driver. Position for the linear actuator is controlled using the potentiometer feedback. Wheel velocity is controlled using quadrature encoders and a movement to omni-wheel speed transformation similar to [22].

The entire system is designed to be portable and fully self-contained. It is powered by a 4-cell LiPo battery pack with a 5000mAh capacity.

Multiple levels of safety features for the infant have been built into the system. At the software level, the operator can issue software emergency E-stop commands over the laptop. An E-stop command issues a stop command for all motors and actuators. If communication with the Control Server is lost, the Motion Control Modules are programmed to stop driving the motors. At the hardware level, a physical E-stop button on the robot cuts power to the motors, causing them to decelerate to an almost immediate stop.

5 Control Laws

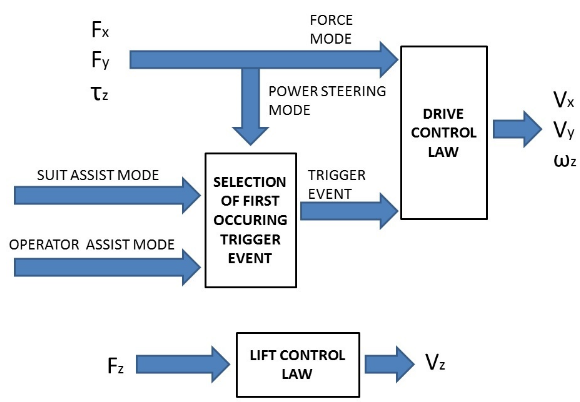

Fig. 8: *Control laws defining how the infant interacts with the robot.*

The mapping of infant actions onto robot motion has been defined by control laws for driving along the floor, and for raising the infant's trunk off the floor (see Figure 8).

There are four drive control modes for motion along the floor. These are force mode, operator assist mode, power steering mode and suit assist mode. The force mode and power steering modes allow control through interactions between the infant and the ground. The suit assist is available for gesture-based control for very weak infants using a motion capture system [23] and a novel gesture-recognition system. The operator assist mode allows the operator to intervene in case the infant drives the robot into a spot that is difficult for the infant to extricate themselves from on their own.

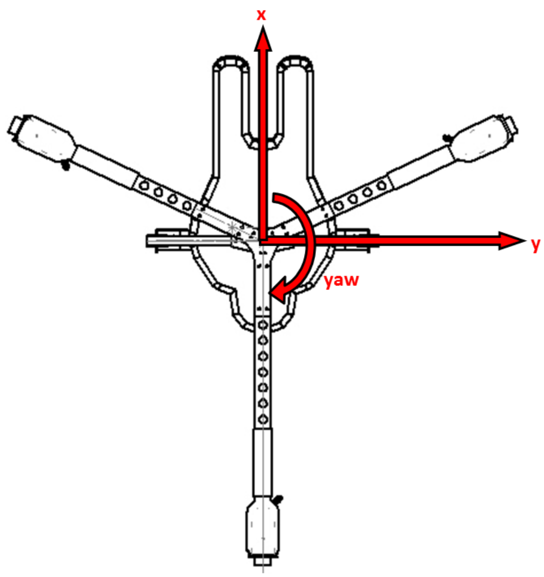

Fig. 9: *Robot frame of reference for control kinematics. The x axis points towards the front of the robot. The z-axis is into the plane of the page.*

These four drive modes can be activated independently, and they work together to generate global robot velocity commands. A generalized equation mapping infant action to global drive velocity commands is provided below; it is used for linear velocities in the x and y directions, and the angular velocity about the z-axis:

$$V_D = K_D F_D + V_A(t) \tag{1}$$

where V_D is the commanded global robot velocity to drive along the floor, K_D is the gain for the force mode, F_D is the driving force or torque induced by the infant, and $V_A(t)$ is the velocity contribution of an "assist event" triggered by the operator assist, power steering, or suit assist modes. $V_A(t)$ is a function of time. Figure 9 illustrates the axes used.

In the force mode, a force or torque generated by the infant generates a component of the global robot velocity. The other three modes compete with each other to generate the other component of the global velocity. This is done by triggering "assist events." In the operator assist mode, an assist event is triggered by the caregiver through the operator laptop. In power steering mode, a force beyond a certain threshold triggers an assist event. In suit assist mode, a gesture recognized by a wearable motion capture system [23] triggers an assist event.

Once an assist event is triggered, a third order minimum jerk velocity pofile is generated for a preset period of time δt_A over a preset distance δs_A. It is followed by a preset refractory period δt_R. During the time $(\delta t_A + \delta t_R)$, other assist events are ignored. For example, if the power steering mode triggers an assist event, a subsequent assist event triggered by the suit assist mode will be ignored.

For lifting the infant off the ground, there is only one mode, which is called the gravity mode. When active, the upward force can trigger an upward movement for the linear actuators. The operator sets a desired lifting force, a force dead band, and a minimum height. If the last δt_L milliseconds have an average lifting force greater than the top end of the band, the linear actuators lift the infant. If the average lifting force is within the deadband, the actuators maintain the current height. If the average lifting force is below the bottom end of the dead band, then the linear actuators settle down towards the preset height.

When gravity mode is deactivated, the preset minimum height is maintained. It can be adjusted at any time through the operator laptop. Currently, the infant's torso can be placed 3-10cm from the floor. The minimum height is the the limit imposed by the padding placed under the infant.

6 Testing

We have measured the minimum magnitude of three different forces that an infant could use to trigger motion in the SIPPC3 (see Table 1). These are based on the thresholds that we have selected to filter out FT sensor noise and undesirable oscillations caused by the dynamics of the robot structure. The uncertainty quoted for each of the forces is based on the measurement bias error and the random error using Student's t-distribution (95% confidence interval). For the moment arm measurements, only the bias error is quoted, since these were not repeated. The *x* and *y* axes are shown on Figure 9.

Table 1: *Force thresholds required to activate the SIPPC3 under force control. F_x is a simulated forward push, $F_{x,offset}$ is a simulated forward push using one hand, and $f_{y,offset}$ is a simulated turning force applied sideways.*

	F_x	$F_{x,offset}$	$F_{y,offset}$
mean force (N)	2.26	2.86	1.78
error (N)	0.120	0.080	0.061
standard deviation (N)	0.168	0.126	0.085
samples	10	12	10

The first of these is the force F_x applied in the forward direction through the center of the robot. This is a force that an infant could use to propel himself or herself forward. The load was applied to the frame by pulling on straps used to attach infants onto the padding. The robot was placed on top of a table and a string was attached to the straps. The other end of the string was run over a smooth pivot over the edge of the table and attached to an empty container. Water was gradually poured into the container to apply an increasing steady force. Once the robot started to move, the container was taken off the string and weighed on balance with $1g$ resolution. The mean threshold force F_x was calculated using acceleration due to gravity as $9.81m/s^2$.

The second force is also a force in x but the line of action is offset from the center. This is similar to a force that an infant could use to propel himself or herself forward using one hand on the floor. From video recordings of infants on the SIPPC3, one line of action of this force is close to the shoulder. For this test, we took it to be one hand breadth away from an infant's shoulder in the y direction. Using mean shoulder breadth and hand breadth data for 6-8 month old infants [24] gave a moment arm of $0.118 \pm 0.063m$. Force was applied in a similar manner as above. To provide a rigid offset point for force application, a metal plate with holes was clamped onto the padding such that one of the holes lined up with the desired line of action of the force.

The third force is a force in y with the line of action offset from the center of the robot. This is similar to a force that an infant could use to push against the floor to turn away. From video recordings, one line of action of such a force is slightly above shoulder level. For this test, we took it to be half the length of the upper arm of 6-8-month old infants. Using anthropometric data from [24], the moment arm about the center of the robot is $0.229 \pm 0.63m$. Force was applied in a similar manner as the $F_{x,offset}$ force above.

We also performed some tests to evaluate smoothness and response time. The motion from an assist event is smooth because the controller uses a minimum-jerk trajectory to generate smooth motion profiles (see Section 5). The motion resulting from the force mode is approximately as smooth as the force applied. For the force mode, we have verified smooth response when applying continuous forces. With infants, however, the motion is not as smooth and continuous. This is because crawling is not a continuous process and infants do not apply continuous smooth forces. We measured the response time of the robot using video footage. The response time is defined as the time interval between the instant the force is applied, and the instant that the robot starts to move. The response time was $120 \pm 18ms$.

In all the above tests, and in all the experimental sessions with infants, there has been no instance of the robot tipping over. The wheels are placed far enough apart and the center of gravity is low enough that an infant cannot tip over the robot.

The robot is currently in use in a study which is planned to test 30 typically developing infants and 20 infants at risk for CP over the next twelve months. Three typically developing infants have completed the study so far using this robot. Subjects start at four to five months and have multiple sessions per week with the robot for the subsequent eight weeks. The subjects are able to learn how to engage the robot in order to reach toys that have been placed for them on the ground. The robot has been approved by IRB as safe for testing with typically developing infants and infants with CP.

7 Conclusions and Future Work

We have described an assistive crawler robot to supplement the efforts of children who have CP or similar conditions. This robot allows shared and dynamically changing weight bearing and it can adjust the height of the baby from approximately 3cm (the thickness of the infant support pad) to 10cm. Together, these features enable the robot to accommodate infants of wide range in height and weight, and let them develop their crawling capabilities in a close-to-natural pose from scooting along the ground to advanced crawling. The holonomic motion capability allows the robot to accommodate turns and motions that are generated by the subjects. These are new capabilities for assistive crawler robots and allow the subjects to learn and develop their prone locomotions skills more naturally.

In addition to traditional methods for monitoring infant development, we are using electroencephalography (EEG)-based neuro-imaging and a wearable motion-capture system (kinematic suit) developed in-house [23]. The kinematic suit can also be used as an interaction interface where an infant's limb motions are used to trigger the robot response. The neuro-imaging with the SIPPC3 is giving additional indications of goal-directed movement [25]. The SIPPC3 body also serves as an advantageous mounting point for cameras to record head, arm and foot movements.

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