Design and Development of an Autonomous Feline Entertainment Robot (AFER) for Studying Animal-Robot Interactions

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***Abstract*—The aim of this paper is to present the design and development of a safe and reliable autonomous cat toy for the purposes of entertaining pet cats when human interaction is not feasible. The proposed Autonomous Feline Entertainment Robot (AFER), an autonomous cat toy, is comprised of a table-mounted base, and a robotic arm with two linkages. The AFER Version 1(v1) has a cat-toy affixed to the end of a linkage as the end effector, while the AFER Version 2 (v2) has a passive joint with a string to which a cat toy end effector is attached. The AFER v1 has 2 Degrees of Freedom (DOF), while the AFER v2 has 3DOF, and both are actuated by servomotors interfaced with an Arduino microcontroller. In order to enable maximum functionality, the AFER is designed with multiple movement patterns or modes for play, as well as the ability to change the specific end effector of the toy. Position control was used for the motion and trajectory planning when developing the movement patterns. The interaction between AFER and two kittens has been evaluated in an experimental scenario, and the results show satisfactory and safe interactions. The AFER can be used as a model for studying effective animal-robot interactions and pet entertainment.**

***Index Terms*——Animal-robot interaction, pet entertainment robot, autonomous cat toy, robot design, design evaluation**

I. Introduction

In 2020, pet adoptions steadily rose and the market for autonomous pet entertainment robots is increased concurrently. Pets require mental stimulation and physical exercise to avoid boredom, anxiety, and poor behaviors associated with under stimulation.

A. Background – Animal Welfare Standards

'The Five Freedoms' were first developed by the Brambell Committee Report in 1965 as the minimum standard for ethical treatment of farm animals. These freedoms are summarized as: freedom from thirst, hunger, and malnutrition; freedom from discomfort; freedom from pain, injury, and disease; freedom to express normal behavior; freedom from fear and distress [1]. From the Five Freedoms, researchers created a framework for assessing the welfare of zoo and lab animals as well. In the case of companion animals, the responsibility for meeting these needs and providing a healthy and engaging environment as well as the environmental enrichment falls upon their owners. The term 'environmental enrichment' can be used to describe "changes, modifications and other interventions made to the environment with the aim of improving the welfare of the animals living in that environment [2]."

B. Problem Identification – Providing Adequate Mental Stimulation for Indoor-only Cats

The American Veterinary Medical Association, Humane Society of the United States, most American animal shelters, and American veterinarians recommend that domestic cats be kept indoors in both urban and suburban living situations. This recommendation considers several factors; outdoor domestic cats can pose a threat to the balance of local ecosystems, and, generally, indoor domestic cats are much healthier and have longer lifespans compared to their outdoor counterparts [2]. Remaining indoors protects the cats from outdoor hazards such as vehicles and predators, however, it also provides a much lower degree of stimulation and sensory engagement than the outdoors. This lack of engagement can lead to boredom, stress, and ultimately destructive behaviors of the cats [3]. Therefore, indoor cats require enrichment activities, yet awareness of enrichment needs is often lacking among pet owners. Some pet owners may find it particularly difficult to meet the sensory and occupational needs of younger cats and kittens, as they tend to have more energy and require more active play time. In order to provide a more enriching environment for these cats, a robot designed to engage and play with the cats could be activated when their owner is otherwise occupied. The robot should provide effective stimulation and engagement, and be safe for the cats. However, there are extremely few reports in the literature investigating effective examples of such entertainment robots for cats or pets.

C. Objectives

This project aimed to develop a robot that could fulfill this purpose. Thus, the objective of this paper is to present the design, development, construction, and evaluation of an autonomous toy-like animal robot - the Autonomous Feline Entertainment Robot (AFER) with its two Versions 1(v1) and 2(v2). The robot developed, built, and tested was intended to entertain two six-month old kittens when they were unable to be attended by a human. The AFER system aims to assist pet owners with meeting their needs towards entertaining their pets.

II. Related Works

A literature review was conducted in several areas to ensure robust design and experimentation practices. Previous robotics studies involving pet-robot interactions were investigated to ascertain the level of previous research conducted for similar or analogous robots. Behavioral studies on cats regarding toy and play preferences were researched to inform robot movement patterns and selection of the cat toy to be used as the end effector.

A. Studies on Pet-Robot Interaction

Two relevant papers on pet entertainment robots and the related pet-robot interaction were available. The first paper was a design innovation exploring a possible design for an autonomous pet care robot intended for dogs [4]. The study provided interesting ideas regarding movement and food rewards, but the robot has not yet been prototyped or tested. The second study focused on various types of robots and their effectiveness when entertaining a cat [5]. This was more directly applicable to our objectives than the first study, offered good insight into robot design considerations specific to cats, and defined the concept of Animal-Robot Interaction (ARI). The model in [4] is the preliminary design for a "home service robot for pet caring." This robot design focused on playing, feeding, and otherwise caring for a dog – a set of functions which are not currently available in any single commercial pet-care robots. The research in [5] aimed to examine the possibility of a robot replacing a human for the purposes of short-term pet care as well as use the definition and practices of Human-Robot Interaction (HRI) to create a working understanding and set of criteria for Animal-Robot Interaction (ARI). The identified differences between HRI characteristics and ARI characteristics largely hinge on the ability of the user to communicate clearly with the robot. Since a human user has the ability to command the robot to complete a certain task, and an animal user does not, a Pet Care Robot (PCR) must have the ability to accept commands from human users and also have adequate sensing and processing ability to interpret pet-provided signals and respond appropriately to the defined pet behavior. Currently, there are no commercially available robots designed for pet interaction that can monitor and adjust functions based upon the emotional state of the pet.

B. Cat Behavioral Studies

Many studies on cat play behaviors have been conducted and in reviewing several of those, movement was consistently found to be one of the crucial components when attempting to elicit play behaviors in cats. Movement was found to be particularly effective when the toy was moved away from the cat or in a manner that mimicked prey [2], [6]. However, examples of effective, real-time and safe interactions between robot toys and cats were limited.

III. Design Requirements

Given the intended use of the AFER platform, the design could not be overly complex and could not require components that would be difficult to acquire for the average person. The robot required the ability to move a cat toy end effector in several, distinct movement patterns for maximum engagement with the animals. The robot design also needed adequate safety precautions integrated into the design to prevent injury during operations. The joints and linkages needed adequate softness to prevent injury in the event that the robot made contact with an animal during the course of operations, and any components relating to the control such as wires would be designed such that the animals will not be able to access them.

IV. Materials and Methods

A. Materials List

The following materials were used to design, assemble, and test the AFER systems: Arduino controller (1), USB Cable (1), CAT 6e Cable (1), a computer with the capability to run Arduino Integrated Development Environment (IDE), Autodesk Fusion 360 Computer Aided Design(CAD) software and Open Source Fritzing Hardware Prototyping Software, a servomotor with 360° rotation (1), High-torque servomotor with 180° rotation (1), Servomotor horn – 4 prong (1), servo horn 2-prong (1), 30 row bread board (1), composite dowel (1) , 3-D printed Polylactic Acid (PLA) *l1*, 3-D printed PLA dowel mount (1), 3-D printed PLA servomotor mounts (2), plywood base (1), wood clamps (2), Cat Toys – Feather (1) / Mouse (1), C-Clamp (2), Bosch 12v Lithium Ion Battery Power Drill (1), IRWIN 15 Piece Drill bit set – sizes $\frac{1}{16}$ to $\frac{3}{8}$(1), String (1), Bolts (10), Superglue (1), Sewing ruler (1), Tape measure (1), 3-D printer – Monoprice Maker Select v2, PLA filament, etc.

B. Methods

The following high-level steps were used:

- Step 1: Design and build the system
- Step 2: Solve the kinematics and Jacobian
- Step 3: Develop and implement movement patterns
- Step 4: Experimental evaluation of the design
- Step 5: Performance Analysis

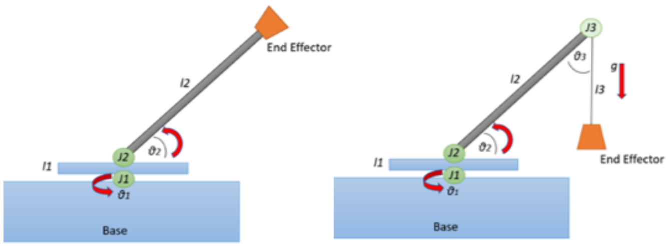

Fig. 1. AFER v1 and v2 sketches.

1) Designing the Robot: The first step in designing the robot was to hand sketch the initial block diagram design for AFER v1 and v2. The hand sketches were then converted to basic diagrams on a computer, shown in Fig.1 below:

For both AFER versions: J1 is the first joint, J2 the second joint, *l1* the height of the rotating platform between J1 and J2, *l2* the length of the actuated arm, θ_1 the angle of rotation about the z-axis, and θ_2 the angle of *l2* with respect to the x-axis. AFER v2 has three additional parameters: J3 as joint 3, *l3* as the length of the string attached to J3, and θ_3 as the angle between *l2* and *l3*. Once the overall design was determined, the pieces requiring CAD rendering - *l1*, servomotor mount 1 (SM1), servomotor mount 2 (SM2), and the dowel mount (DM) – were sketched by hand. Once sketched, measurements of the servomotors and dowel were taken using a sewing ruler and tape measure. Those measurements were then used to inform the exact size and shape of the part builds. The Autodesk Fusion 360 software was used to build and render each of the parts. Fig.2 shows the CAD rendering and completed print of the SM1 piece, as an example.

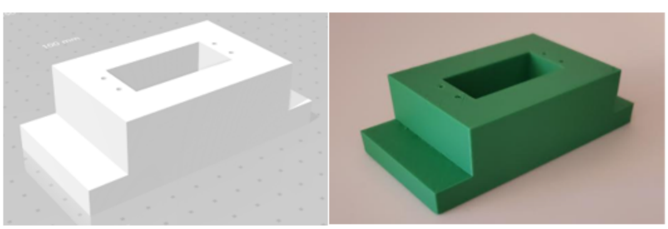

Fig. 2. AFER SM 1 CAD rendering (left) and printed piece (right).

2) Building the Robot: When designing the pieces to be 3-D printed, there were sets of bolt holes that were not rendered in CAD to allow greater flexibility while assembling and to allow for adjustments to ensure proper alignment of the axes. The necessary holes for those bolts were measured and drilled individually during the assembly process. The robot was built beginning with the topmost piece and working down to the base to simplify the process of establishing the z-axis for joints 1 and 2 as coincident. On the front plate, a hole was drilled at a height that would ensure the center axis of the dowel would intersect orthogonally with the rotational axis of J2, and the servomotor horns were screwed into DM. Servo Mount 2 (SM2) was then mounted to the side of *l1*, positioning J2 directly above J1 to avoid altering the z axis. A wiring port and inset bolt holes were also drilled into SM2. A similar process was used on *l1*. The high torque servomotor was then fitted into SM2 and attached using the printed bolt holes; once secured to the mount, the servo was connected to DM. Subsequently, the 360°rotation servomotor was fitted and bolted into the mount. Mounting the 4-prong servomotor horn to *l1* was accomplished using super glue and screws. The SM2, DM, *l1* configuration was placed onto the servomotor in SM1 once the glue had dried. The final build step was to attach the AFER robot to the plywood base. The same 3-D printed core parts were used for both v1 and v2; to switch between versions, the directly connected end effector was replaced with a string and the end effectors were then attached to the string. Fig.3 shows the fully assembled AFER v1 and v2.

Fig. 3. Fully assembled AFER v1 (left) and v2 (right).

Wiring for the Arduino and two servomotors was accomplished by stripping the CAT 6e cable and using the interior wires to connect between Arduino ports, the bread board, and the positive, negative and control wires for both servomotors. To ensure adequate power for running multiple servomotors, the bread board was connected to an external 5v power source. Fig.4 is a wiring diagram built using an open source wiring tool called Fritzing to illustrate the connections needed to power and control the AFER core configuration and subsequently, AFER v1 and v2.

3) Solving the Kinematics and Jacobian: The process for solving the kinematics is described in greater depth in Section V. The process for deriving the Jacobian for AFER v1 and v2 is described in Section VI.

4) Developing and Implementing Movement Patterns: The movement patterns selected were a simple back-and-forth oscillation, an up-and-down oscillation, and a combination of both types of oscillation. Position control was used for all three movement patterns. The Arduino Servo Library contains a function "Sweep" which swings the shaft of the servomotor back and forth across a 180° arc. The source code for this function was used as a starting point for both the up-and-down and back-and-forth oscillation patterns [7]. Each oscillation pattern was comprised of two loops, one to sweep the servo from 0 to the maximum angle - 45° for servo 2 and 180° for servo 1 – and a second loop to sweep the servo from the maximum angle back to 0. The combination of both oscillation patterns was achieved by combining the four loops from the previous code into two loops that actuated both

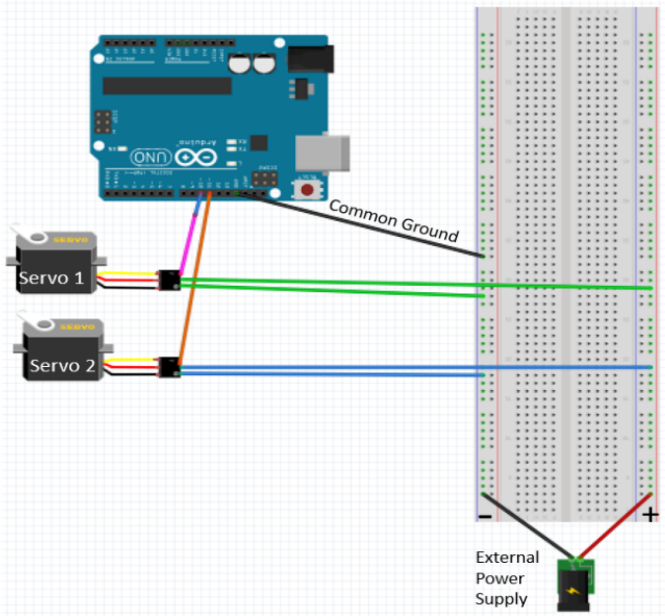

Fig. 4. AFER Circuit Diagram.

servos simultaneously. All three of those motion patterns were simplistic and did not require any complex path planning or trajectory generation to implement. To avoid erratic robot behavior during initial testing, the robot pieces were separated, and the code was tested on the servomotors with no load. The initial testing involved sweeping servo 1 in a 90° arc and servo 2 in a 45° arc; the testing with those parameters was successful. The code was then tested on the full common core unit. Upon initial assembly and motion testing, the servo horn and motor at J1 continuously became disconnected after 2-3 oscillations. To add stability, the horn and motor were superglued together. Once the glue dried, J1 was significantly more stable and able to withstand the necessary continuous oscillation. Once AFER was securely assembled, it became clear that 180° was too large of an angle for servo 1 when accounting for the full length of *l1* and space in which the kittens could play; the sweep angle for servo 1 was, therefore, reduced to 90°. Additionally, to resolve an increment error, the servo 1 code was updated to increment by 2 rather than 1.

5) Test Subjects: The robot was tested on two kittens – one male, one female – each approximately six months old. The female kitten, named Klunk, was solid black; she weighed 6.1lbs at the time of testing. Her demeanor was timid and easily startled. The male kitten, named Traximus, was black with white tuxedo markings; he weighed 6.4lbs at the time of testing, and his demeanor was outgoing and curious.

6) Experimentation and Testing (Evaluation) : Once fully assembled, the robot was tested to ensure that it could be operated effectively and safely prior to the introduction of the test subjects. The experimentation and test procedures are documented in greater depth in Section VII.

7) Safety Considerations: The robot was designed with the following safety considerations:

- The Servomotors selected do not create adequate force to cause damage to the kittens.
- The dowel selected was made of partially compliant material that was unlikely to cause injury if it collided with the one of the kittens.
- Trajectories that simulated a wrapping movement were avoided to minimize the likelihood of accidentally tangling the kittens in the AFER v2 string.
- For AFER v1, the robot was placed on a box and secured with C clamps to prevent it from falling.
- For AFER v2, a set of C clamps were used to secure the robot base to a table and ensure the kittens could not pull the robot onto themselves during play and cause injury.
- The wires used to connect the robot and laptop were covered with cardboard or paper as much as possible to prevent the kittens from chewing the wires as well as protect from accidental shocks.

8) Performance Analysis: Performance of the robot was ascertained predominately by visually observing the behavior of the system and the test subject's reactions to it. Some servo data was observed in the Arduino Serial Monitor to verify the system movement patterns were implemented properly. See Section VII for further details.

C. Assumptions

The design and modeling assumptions are below:

- The encoders in the servomotors had sufficient precision for this task
- For v1, all linkages were modeled as rigid linkages
- For v2, J3 was modeled as a passive joint that was frictionless, had no damping, and had no elasticity
- For v2, the link between J3 and the end effector was assumed to be rigid
- For both robots, when solving the kinematics, static stability would be assumed at all points

V. Kinematics

For both versions of the robot, the transformation matrix values were determined using Denavit–Hartenberg (DH) parameters. When solving the kinematics for both v1 and v2, the length of the common normal was identified by the variable r to avoid confusion between variables a and α.

A. Robot Configuration Overviews

AFER v1 was a 2-DOF robot, actuated by servomotors and an Arduino controller, and modeled such that the cat toy end effector formed a rigid linkage with *l2*. The robot utilized a revolute base joint (J1) and a revolute lift joint (J2) to move the end effector as commanded; the chosen joint configuration allowed the robot to operate along the edges of a hemispherical work envelope with a surface area of $39.9ft^2$, situated about the robot's center, shown in Fig.5.

For this version of the robot, the end effector was mounted directly to *l2*. As the arrangement caused no considerable difficulty when solving the kinematic equations, the mathematical modeling used for v1 closely resembled the real-world

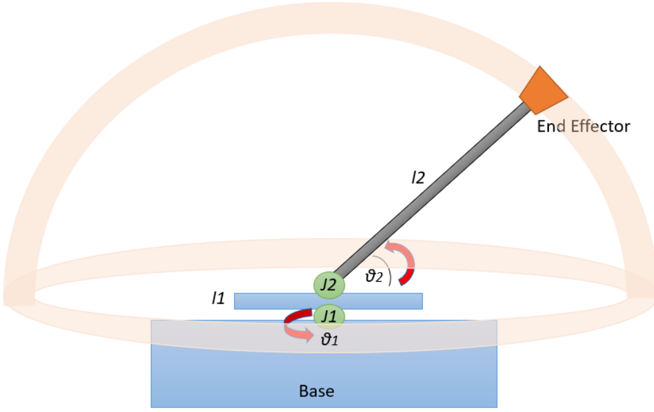

Fig. 5. AFER v1 Work Envelope.

robotic build, and the assumptions when solving the kinematic equations were minimal. For AFER v2 as shown in Fig.6, the cat toy end effector attached to the rest of the robot via J3, a frictionless joint that was passive in the pitch direction and had no damping. The chosen joint configuration allowed the robot to operate along the edges of a hemispherical workspace with a surface area of $39.9ft^2$, situated about the robot's center. The workspace size of v1 and v2 were identical, however the v2 workspace was lower due to the introduction of *l3*.

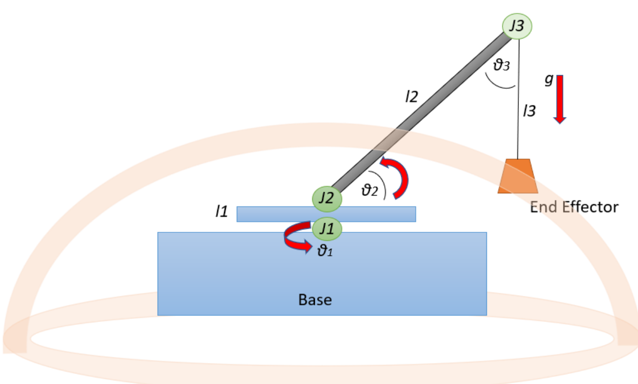

Fig. 6. AFER v2 Work Envelope.

Realistically, the string attached to the J3 joint on AFER v2 was able to move freely and had factors such as elasticity and conflicting multi-modal vibrations. However, it caused the kinematic equations to be non-linear and extremely difficult, if not impossible, to solve. Therefore, in order to ensure that the kinematics for this version of the robot were useful and solvable, J3 was modeled as a passive joint on a rigid link instead of a compliant linkage. Additionally, the momentum was discounted and the gravity(g) was assumed to be the only force acting upon the suspended end effector.

B. AFER v1 Forward Kinematics

The forward kinematics for v1 as a 2-joint robot were relatively simple, but to ensure the solvability of the kinematic model, static stability was assumed for all points. Using the coordinate frames as shown in Fig.5, creating a transformation matrix from the base of the robot to the end effector using a link coordinate diagram was straightforward. The transformation values of r, α, d, and θ are given in Table I.

TABLE I
DH PARAMETERS FOR AFER v1

Point	d_i	θ_{DHi}	r_i	α_i
J1	0	0	0	0
J2	*l1*	θ_1	0	0
EE	*l2*	0	0	θ_2

AFER v1 had a horizontal stroke equal to the length of *l2* and a vertical stroke of *l1* + *l2*. Additionally, the absence of linear actuators indicated that the di values were static. The transformation from the coordinate frame at J1 to the coordinate frame at the end effector was determined as shown in (1):

$$\begin{bmatrix} cos\theta_1 & -sin\theta_1 cos\theta_2 & sin\theta_1 sin\theta_2 & 0 \\ sin\theta_1 & cos\theta_1 cos\theta_2 & -cos\theta_1 sin\theta_2 & 0 \\ 0 & sin\theta_2 & cos\theta_2 & l2 + l1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

C. AFER v2 Forward Kinematics

The forward kinematics for AFER v2, a 3-joint robot, were relatively simple. When solving the kinematics, static stability was assumed. The DH parameters for J1, J2, and J3 in v2 were identical to the DH parameters for J1, J2 and the end effector (E) of v1 due to the common core configuration of the robot. The values for v2 DH parameters are listed below in Table II.

TABLE II
DH PARAMETERS FOR AFER v2

Point	d_i	θ_{DHi}	r_i	α_i
J1	0	0	0	0
J2	*l1*	θ_1	0	0
J3	*l2*	0	0	θ_2
E	-*l3*	0	0	$\theta_2 + \frac{\pi}{2}$

As in v1, v2 had a horizontal stroke equal to the length of *l2*; however, the vertical stroke of *v2* was equal $l1 + l2$–*l3*. Given that there were no linear actuators, the d_i values were static. The transformation from the coordinate frame at J1 to the coordinate frame at the end effector(E) for v2 was determined as shown in (2), where $(\alpha_E = \theta_2 + \frac{\pi}{2})$.

$$\begin{bmatrix} c\theta_1 & -s\theta_1 c\theta_2 c\alpha_E + s\theta_1 s\theta_2 s\alpha_E & s\theta_1 c\theta_2 s\alpha_E + s\theta_1 s\theta_2 c\alpha_E & -l3 s\theta_1 s\theta 2 \\ s\theta_1 & c\theta_1 c\theta_2 c\alpha_E - c\theta_1 s\theta_2 s\alpha_E & c\theta_1 c\theta_2 s\alpha_E - c\theta_1 s\theta_2 c\alpha_E & 0 \\ 0 & s\theta_2 c\alpha_E + c\theta_2 s\alpha_E & -s\theta_2 c\alpha_E + c\theta_2 s\alpha_E & -c\theta_2 l3 + l2 + l1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

D. AFER v1 Inverse Kinematics

Based upon the hemispherical geometry and low degrees of freedom present in v1, it was simple to solve for the joint angles based on the position of the end effector. Basic trigonometric functions were leveraged to solve for θ_2. Since the high torque servomotor creating θ_2 had a maximum range of $180°$, there was only one solution as in (3).

$$\theta_2 = sin^{-1}\frac{E_z - l1}{l2} \quad (3)$$

It was easiest to solve for the rotational joint at θ_1 by projecting J1 into the x_1, y_1 plane. This allowed the rotational displacement of the joint to be calculated using the simple trigonometric relationships. Due to ambiguity when solving with inverse cosine, inverse tangent was selected for solving for θ_1. Since the servomotor at J1 could rotate a full $360°$, there were two possible solutions for this joint angle, as (4) and (5) show.

$$\theta_1 = tan^{-1}2(E_x, E_y) \quad (4)$$

$$\theta_1 = \pi + tan^{-1}2(E_x, E_y) \quad (5)$$

E. AFER v2 Inverse Kinematics

For θ_1 and θ_2, the v2 inverse kinematics was identical to the v1. Solving for θ_3 was trivial using the mathematical properties of triangles. Given that the sum of the interior angles of a triangle are always equal to $180°$, and the assumption of static stability for J3, (6) was used to define θ_3:

$$\theta_3 = \frac{pi}{2} - \theta_2 \quad (6)$$

VI. Jacobian Matrix

The Jacobian matrices for AFER v1 and v2 were solved in order to provide insight on the relationships between the joint space and Cartesian space when planning the movement patterns. The Jacobian was determined by using standard spherical-Cartesian transformation equations as in (7), and the substitution values for v1 were $\theta = \theta_1$, $\phi = \theta_2$, and $r = l2$.

$$\begin{bmatrix} sin\theta_2 cos\theta_1 & l2cos\theta_2 cos\theta_1 & -l2sin\theta_2 sin\theta_1 \\ sin\theta_2 sin\theta_1 & l2cos\theta_2 sin\theta_1 & l2sin\theta_2 cos\theta_1 \\ cos\theta_2 & -sin\theta_2 & 0 \end{bmatrix} \quad (7)$$

The Jacobians for AFER v1 and v2 were identical due to the common core configuration between AFER v1 and v2 and the assumptions regarding J3 in v2. The Jacobian matrix for joints 1 and 2 remained unchanged, and supposing static equilibrium, velocity at the end effector along the y axis will always be zero. The end effector velocity along the x axis could change and, given that the value of θ_3 was dependent upon θ_2, would always change at the same rate as the velocity at J3. As a result, the Jacobian in (7) sufficed for AFER v2 as well.

VII. Experimental Evaluation of Performance

Testing the fully assembled robot was conducted in two analogous but distinct phases, one for each configuration of AFER. Phase 1 tested the performance of AFER v1, and Phase 2 involved the same testing for AFER v2. The testing questions answered for both versions are listed below:

- Is the base adequately secured?
- Does the up/down oscillation function under load?
- Does the left/right oscillation function under load?
- Does the combined oscillation function under load?
- Do the chosen trajectories avoid self-collision?
- Are the wires adequately concealed?
- Have all obstacles been removed from the area?
- Is the end effector securely attached?

Results for all tests were collected using visual observation, and servo outputs. Visual observation was the primary method of ascertaining proper behavior of the system, however the servo output data was also analyzed in real time to verify proper operation of the robot. Once the robot was determined to be operational and safe, the test subjects were introduced. The following procedure was used to ascertain the test subject's interaction preferences between AFER v1 and AFER v2 robots and the type of end effector. Those steps were recorded and evaluated based on visual observation:

- Introduce test subjects (cats) to base configuration
- Assemble AFER v1
- Introduce test subjects to v1 configuration
- Allow test subjects to interact with operational AFER v1 with End Effector 1 attached
- Allow test subjects to interact with operational AFER v1 with End Effector 2 attached
- Observe and record test subject behavior
- Repeat steps 2-6 with the AFER v2 configuration

Fig. 7 shows the engagement of kittens with AFER v1 and v2. Basic standards for ethical treatment of animals were obeyed when observing the cats/kittens engaged with the robots [1].

Fig. 7. Kittens engaged with AFER v1 (left) and v2 (right).

VIII. Results and Performance Analysis

Initial testing of movement patterns on the completely assembled robot was extremely successful, and the robot followed the linear movement pattern as expected. Introducing both kittens to the base configuration and AFER v1 configuration was simple and uneventful. Neither animal exhibited any of the common fear or stress reactions – ears flattened, sitting low, hiding or hissing – and both engaged with the end effector toy once the robot was in motion. For the analysis of the pet-robot interaction shown in the tables below, Active Engagement (AE) was defined as the kitten chasing and catching or attempting to catch the end effector; Passive Engagement (PE) was defined as the kitten watching and showing interest in the robot or end effector, but not attempting to chase or catch. No Engagement (NE) was used to describe time in which the kitten was completely disinterested in the device. Engagement behaviors were observed over a 5-minute experimentation period. Comparisons of engagement for AFER v1 is shown in Table 3.

TABLE III
AFER v1 INTERACTION

Kitten	AE	%AE	PE	%PE	NE	%NE
Male	45s	15%	3min25s	68%	50s	17%
Female	3min45s	75%	45s	15%	0s	0%

The kittens were also not frightened by the AFER v2 configuration, however, the female kitten seemed more wary and the male kitten dominated the play window. Of the 5 minutes allotted for testing, only 2 minutes were completed prior to the failure of the J1 joint. Time of engagement is shown in Table 4.

TABLE IV
AFER v2 INTERACTION

Kitten	AE	%AE	PE	%PE	NE	%NE
Male	2min	100%	0s	0%	0s	0%
Female	0s	0%	2min	100%	0s	0%

The J1 failure occurred when the top portion of the robot including J2 and *l1* separated from the base and J1 at the servomotor-servo horn connection. Despite the superglue used at that connection, the force created by the kittens playing with the end effector was too much for the robot to withstand. Testing of the robot was halted at this point and repairs were attempted. Although testing was cut short, both versions of the robot proved viable concepts, and highly interesting to the kittens. Both kittens engaged with both versions of the robot, though each seemed to have a distinct preference in version.

IX. Potential Impacts

The primary goal and impact of this research was to increase the environmental enrichment of a home thereby increasing the health and happiness of two kittens residing there. These kittens now have greater access to a safe and engaging non-static toy. This impact has a broad applicability and, with further work, has the capacity to impact and positively influence on the well-being of other cats as well. The market for robotic toys for entertaining pets is growing rapidly and a robot such as AFER meets many of the necessary requirements for a robotic pet toy and has the potential for monetization. Monetizing or selling the robot design to a commercial entity for mass production would allow other pet owners to provide a higher level of engagement to their pets as well. This would be particularly useful during crisis situations similar to COVID-19, as the pandemic caused an unprecedented increase in individuals fostering or adopting pets from animal shelters [8]. Therefore, a large number of first-time pet owners and individuals with multiple pets could highly benefit from having robotic toys like the one presented herein to assist with the enrichment and mental stimulation of their pets.

X. Limitations

There were considerable limitations to this work including lack of access to a robotics lab due to COVID-19 restrictions; as a result, this robot was developed, built, and tested, entirely with at-home robotics equipment. This severely limited the choice of materials and opportunity to attempt multiple builds. Additionally, several necessary base assumptions made limited the scope and real-world applicability portions of the work, particularly for the v2. The assumptions for J3 were significant, yet necessary given the circumstances. As a result, the mathematical model for AFER v2 was not able to account for random motion or vibrations of the string, and, therefore, it was not possible to account for those disturbances while planning movement patterns. Additionally, the lack of an encoder on the passive joint, J3, meant that interpreting the success of the movement patterns in any way other than visual, was not possible. Finally, the preference analysis conducted was based on only two cats and the testing was not repeated multiple times to ensure consistency. A much larger sample size with repetitive testing events would be needed for robust, statistically significant analysis on animal preferences between movement patterns and end effectors [9].

XI. Conclusions and Future Work

A. Conclusions

We developed a simple entertainment robot (two versions) to entertain animals (cats) when they are not attended by humans. Despite limited access to materials, the concepts of the robots were shown to be viable, and the kittens/cats were safely engaged and enjoyed playing with the toy actuated by the robot for as long as the robot was operational. The study is new in the robotics field and possesses significant potential to be used enormously to enhance the entertainment, companionship, and well-being of companionship animals.

B. Future Work

As expected, prototype models of systems had many issues and often required multiple redesigns and repairs; the AFER systems were no different. Unfortunately, redesigns and more robust construction were beyond the scope of the research in its current iteration. The following issues were identified with the design and would need to be addressed in any future work.

The connection at J1 was small and unstable, and a structural redesign of the robot with a more robust joint or additional support material is necessary for any further work. A redesigned system in conjunction with improved modeling procedures would enable refinement of the control algorithm, and lead to better performance. Additionally, implementing more complex movement patterns would increase applicability. Due to the nature of the end effector attachment on v1, the computer and electrical components of the system needed to be placed on the ground. For a system that is expected to entertain pets, this is not acceptable. In future iterations, implementing control with a localized chip and batteries would be ideal. If this is achieved, the AFER base could be mounted on a mobile robot unit for further autonomous functionality.

The interactions between cats and the robots will need to be videotaped, which will allow further analysis of the behaviors of the cats with the robots. Machine learning methods such as the reinforcement learning, inverse reinforcement learning or deep reinforcement learning will be used to learn the behaviors of the cats with the robots, which may suggest significant improvements in the design and controls of the robots.

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