Control of Human Pupil Servo-mechanism with Retinal Light Flux Oscillations

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Abstract

In this research project, we aimed to develop an affordable control system to regulate the human eye's servomechanism response to light. Understanding the mechanisms of human body organs, especially the eye, can lead to better insights into their defects and potential treatments. The human eye's response to light, particularly how the pupil adjusts to different light intensities, was the focus of our study. We sought to construct a system capable of recording and analyzing the changes in pupil diameter when exposed to varying light intensities. The human eye's response to light operates as a servomechanism, where the pupil constricts under bright light and dilates under low-intensity light. By understanding these responses, we can develop treatments for vision defects. Our approach utilized a high-definition, affordable camera to capture changes in the pupil's diameter when subjected to light of different frequencies and intensities. We employed soft lights of varying colors to create a series of light frequencies that induced different responses in the eye. Our system's design was straightforward yet effective. It involved a camera for recording pupil diameter changes and light sources to simulate different lighting conditions. This setup allowed us to monitor and analyze the eye's responses in real time. We recorded the data and used it to understand the pupil's behavior under specific environmental conditions. The recorded data included the diameter of the pupil and the corresponding light intensity, which served as input and output parameters for our control system. We developed a control system that could predict the pupil's response based on the recorded data. The system used the difference between the input (desired light intensity) and the output (recorded pupil diameter) to actuate the control mechanism. This feedback loop allowed the system to adjust the light intensity to achieve the desired pupil diameter, effectively mimicking the natural servomechanism of the eye. Our results showed that the system could accurately predict and control the pupil's response to various light intensities. The system demonstrated stability and minimal overshoot, indicating that it could reliably manage the pupil's servomechanism. The ability to predict the eye's behavior under specific conditions makes this system a valuable tool for both medical research and practical applications in treating eye-related conditions. The significance of our research lies in its affordability and effectiveness. Traditional methods of studying the eye's response to light often involve complex and expensive equipment. Our system offers a cost-effective alternative without compromising accuracy or reliability. This accessibility can lead to broader applications in medical research and education, allowing more researchers to explore and understand the eye's mechanisms. In addition to its affordability, our system's design is user-friendly and easy to implement. It does not require extensive training or specialized knowledge to operate, making it accessible to a wider audience. This simplicity, combined with its effectiveness, enhances its potential for widespread use. The implications of our findings extend beyond the scope of this project. By providing a reliable and affordable means of studying the eye's servomechanism, our system can contribute to advancements in ophthalmology and related fields.

Keywords: Servomechanism, Pupillary light reflex, closed-loop feedback, Human pupil servo-mechanism.

1. INTRODUCTION

The pupillary light reflex is a fundamental physiological response where the human pupil adjusts its size in reaction to light exposure. This paper explores the medical aspects of this reflex and delves into the control mechanisms governing the eye's servomechanism. The reflex involves both pupils constricting when light falls on one eye, a phenomenon known as the consensual light reflex. This detailed examination sheds light on the functioning of the pupil as a servomechanism and the techniques employed to measure human responses to light. Understanding the pupillary light reflex is crucial for studying eye diseases and developing potential treatments. Our objective is to design a control system that manages the servo-mechanistic actions of the pupil by inducing retinal light flux oscillations. This system aims to predict and control changes in pupil size in response to varying light intensities.

The pupillary light reflex causes the pupil to constrict or dilate based on the intensity of the light source. Bright light triggers the sphincter muscles at the pupil's border to contract, reducing its size, whilelow-intensity light prompts the dilator muscles at the iris border to expand the pupil. When light is directed at one eye, such as the left, the pupil contracts in a direct light reflex. In a healthy pair of eyes, the right eye also contracts, demonstrating the consensual light reflex. This coordinated response results from the interconnected efferent and afferent pathways of both eyes. The efferent limb carries signals from the eye to the brain, and the afferent limb transmits signals from the brain back to the eye. For instance, when light is directed at the left eye, the efferent limb sends signals to the brain, which then sends signals through the afferent limbs to constrict both pupils. This interconnected pathway ensures a synchronized response to light exposure. Our proposed control system leverages this understanding to manage the eye's servomechanism effectively. By accurately predicting and controlling the pupil's response to light, the system aims to improve our understanding of the eye's mechanisms and contribute to the development of treatments for vision-related conditions. This research represents a significant step forward in ophthalmology, providing a foundation for more advanced studies and practical applications in vision science. [1]

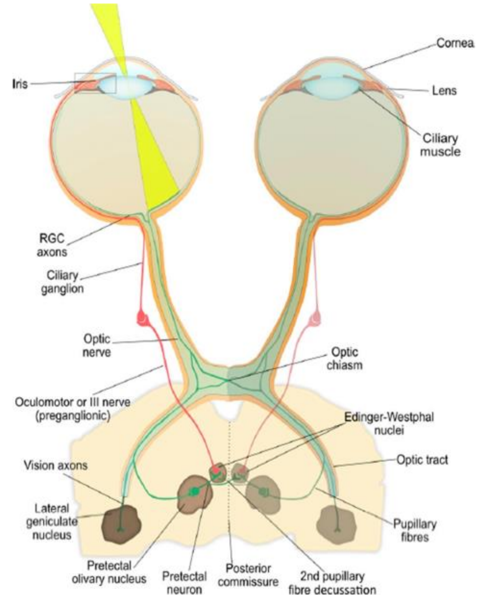

Figure 1: Parasympathetic pathway of human eye [1]

A lot of biological processes can be termed servo mechanisms. The human eye reflex to light can be studied as a servomechanism. Here, the human eye is considered as a control system and a reference light source is considered as input. The controlled light is used as a correcting factor for feedback. An infrared light source throws light at the eye, and the response of the eye is measured through another filter. The diagram illustrates the servo-loop for the human eye's response to light. The light falling on the retina of the eye is the reference light flux quantity which is compared with input light and their difference actuates the control system. The control system then varies the size of the pupil, which changes the controlled light. Thus, by controlling L_C we can change the actuating difference and control the error between the desired input and the present output. [2]

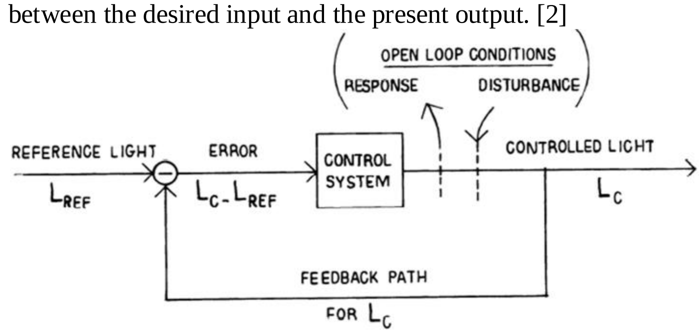

Figure 2: A schematic human eye as a servo-mechanism [2]

Stability, Oscillations, and Noise in the Human
The human pupil reflex to light has been thought to be a self-regulating servomechanism. A designed pupillometer was used for quantitative measurements in animals and human subjects with an intact central nervous system. The pupillometer generates light stimuli that are controlled electronically. For the determination of pupil response, sinusoidal light intensity changes were instilled in an open-loop manner. The pupil servo shows stability with an 18db attenuation slope. In another experiment, gain was artificially increased to instil unstable oscillations whose frequency could be anticipated from a low gain transfer function. Some experiments show noise in pupil response. This noise is not an error in the apparatus or the experimental arrangements of human subjects, but is administered in the loop by another part of the brain. [3] The calculations from this study give the transfer function for human pupil as follows;

$$G(s) = \frac{0.16e^{-0.18s}}{(1+0.1s)^3}$$

The following is the relationship between the closed loop transfer function and the open loop transfer function;

$$F(s) = \frac{G(s)}{1+G(s)}$$

Using neurophysiological and anatomical findings, a non-linear delay differential equation for the pupil light reflex with negative feedback is derived. As the reflex's gain or time delay increases, a supercritical Hopf bifurcation in the pupil area occurs, transitioning from a stable fixed point to a stable limit cycle oscillation. To determine the criteria for instability, as well as the period and amplitude of these oscillations, a Hopf bifurcation analysis is used. The numerical simulations of the model did not produce the more complicated waveforms associated with higher-order bifurcations. This model provides a general framework for studying the various dynamical behaviors induced by the pupil light reflex, such as edge-light pupil cycling. The pupillary constrictor muscle, which has a circular structure and is innervated by parasympathetic fibers, causes pupil constriction. The motor nucleus for this muscle is the Edinger-Westphal nucleus, which is located in the oculomotor complex of the midbrain. [4]. We investigate spontaneous oscillations in a second-order delayed-feedback shunting model of the pupil light reflex. In a straightforwardly manner, this model describes the nonlinear characteristics of the iris and retinal sections of the reflex circuit. In the case of smooth negative feedback, linear stability analysis is used to determine the optimal conditions for a Hopf bifurcation in the pupil region as a function of various neurophysiological system factors such as time delay and neural connection strength. In addition, we investigate oscillation initiation in the presence of piecewise negative feedback and present an analytical expression for oscillation time. Finally, complicated periodic behavior is shown to emerge in the presence of mixed input. The experimental technique known as clamping is an important way of inducing spontaneous oscillations in the eye.

In a second-order delayed-feedback shunting model of the pupil light reflex, we investigate spontaneous oscillations. This model simply describes the nonlinear characteristics of the iris and retinal parts of the reflex circuit. Linear stability analysis is used in the case of smooth negative feedback to determine the best conditions for a Hopf bifurcation in the pupil area as a function of various neurophysiological system parameters such as time delay and neural connection strength. In addition, we investigate oscillation initiation in the presence of piecewise negative feedback and present an analytical expression for oscillation time. Finally, sophisticated periodic behaviour is shown to occur in the presence of mixed input. The experimental technique known as clamping is an important way of inducing spontaneous oscillations in the eye. [5]. We present a unique mechatronic system for automated corneal cross-linking (CCL) treatment in keratoconus patients. Keratoconus is a dangerous disease that, if left untreated, can cause severe visual impairment. The CCL procedure, which is the most promising treatment for this condition, is currently done by hand. The designed automated system is the first of its kind to automate treatment with visual feedback, and it promises to increase treatment efficiency while removing potential side effects and hazards. To track the patient's eye, the system includes a camera, an image processing algorithm built on OpenCV sharp, a planar servomechanism system made up of several mechanical and electronic components, and a PIC microcontroller with digital PID controllers. Before being manufactured, the proposed system and algorithms are built and simulated in MATLAB, and numerous experiments with an eye pattern and animal eyes are carried out. The results are presented and discussed. [6]. Analogies between servo control analytic techniques and a physiologically appropriate nonlinear delay-differential equation (DDE) model for the pupil light reflex are demonstrated. This DDE is compatible with the measured open-loop transfer function, providing physiological insight into the gain and characteristics of the reflex. According to a Hopf bifurcation analysis of the DDE, when the first mode of the characteristic equation becomes unstable, a limit cycle oscillation in pupil area occurs, with its period matching experimental measurements. More modes become unstable after the initial point of instability, corresponding to successive encircling of (-1, 0) on the Nyquist plot, which significantly influences the oscillation's shape. Bifurcation analysis can supplement servo control analytic methods for studying oscillations caused by nonlinear neural feedback processes. [7].

The Form of the Human Pupil: The purpose of this research was to define pupil morphology in healthy human participants. Pupil photographs were taken using a modified slit lamp under steady illumination and 10-20 seconds after darkness. After projection and scanning of transparencies, the pupil margin was represented as a circular Fourier series, and best-fit ellipses were identified. The position of the pupil relative to the limbus was also determined in several cases. The results from 23 participants showed an average pupil non-circularity of 0.0166 in both darkness and light (a value of 0.0200 is discernible with the unaided eye). The best-fitting ellipse accounted for over half of the non-circularity (59.6% in darkness and 47.7% in light). The first four or five harmonics contributed the most to the shape. Shapes were usually consistent throughout a session and could last for at least a year, though there was variation between subjects, especially in light conditions. [8]. Human perception significantly impacts medical image inspection, but little is known about whether professionals' cognitive processing differs or what visual strategies they use while viewing medical images. To address this, we conducted an eye-tracking experiment on three groups of volunteers with varying levels of medical knowledge, collecting data on eye movement and verbal descriptions. Each participant viewed and described 42 dermatological images. Within each expertise-specific category, we designed a hierarchical probabilistic framework to extract common and unique eye movement patterns from participants' fixation and saccadic eye movements. Expert annotations of thought units on recorded verbal descriptions were time-aligned with these eye movement patterns to identify semantic interpretations. This work reveals how participants adjusted their viewing strategies during inspection and extracts their perceptual knowledge for advanced medical image interpretation. [9]. A Neural-Network-Based Approximation

The foundation of a discrete-time nonlinear servomechanism feedback controller lies in solving a set of nonlinear functional equations known as discrete regulator equations. However, due to system nonlinearity, exact solutions to these equations are often unavailable. This research proposes using a feedforward neural network to approximate solutions to the discrete regulator equations, providing a realistic solution to the discrete nonlinear servomechanism problem. The effectiveness of this method was demonstrated using the well-known inverted pendulum on a cart arrangement. Simulation results show that the proposed control law outperforms the standard linear control law. The structure of this paper is as follows: Section II discusses the background of the nonlinear servomechanism problem and explains the concept of nonlinear servomechanism approximation solutions. Section III presents our key findings, while Section IV details a gradient-based strategy for calculating required weights and applies our method to the inverted pendulum on a cart system. Finally, Section V concludes with observations. [10]

A Nonlinear Universal Servomechanism:
A servomechanism problem of controlling a scalar output variable to track any reference signal from some prescribed function space while maintaining internal states bounded is addressed for a class of uncertain nonlinearly perturbed, single-input, single-output, minimum-phase, relative degree-one, linear systems with nonlinear actuator characteristics (encompassing, for example, hysteresis and dead-zone effects). Only the graph of a properly regular set-valued map can contain the actuator properties. For arbitrary prescribed A > 0, a (adaptive) feedback strategy that ensures the tracking error is asymptotic to the interval [-A, A] C R for every reference signal of class R and every system (unknown to the controller) of class S is sought. For feedback, only the reference signal and scalar output instantaneous values are available. The space (R) as the set R of admissible reference signals and rather mild assumptions on the nature of the system nonlinearities are used to create one such universal adaptive feedback solution to this servomechanism

problem. Feedback is continuous, and its evolution is not based on an internal model principle. [11]. Modern deterministic linear regulator and servomechanism theories either neglect system disturbances entirely or presume they can be represented as initial conditions on the plant state variable. When the system is subjected to persistently acting disturbances, controllers constructed using such theories may fail to achieve performance specifications. In this study, we illustrate how existing regulator and servomechanism theories can be modified to account for the presence of persistent fluctuating disturbances. This enables the development of a deterministic controller capable of maintaining set-point regulation or servo tracking in the face of a wide variety of genuine external disturbances. Furthermore, we show how to systematically capitalize on any beneficial effects that may exist in the action of external disruptions. Finally, one can argue that the influence of disturbances on plant response is not always wholly unwanted, and that part of the disturbances' action may be advantageous in achieving the primary control task. [12]. The compensator identification challenge for feedforward and robust control of a general servomechanism problem will be addressed in this study. To change the robust controller, some one-dimensional "on-line tuning" is required, which can be regarded of as a generalization of the conventional single input-single output example. The study's central premise is that the requirements for the existence of a servomechanism controller and the actual controller structure can be expressed in terms of the plant's steady-state gain parameters, which can be obtained easily experimentally. The following is how the paper is organized: Section 1 contains some preliminary results; Section 2 describes how the steady-state gain parameters in Experiments 1 and 2 are determined and deals with the feedforward controller case (Theorem 1); Section IV deals with the robust feedback controller case (Theorem 2) and describes how the controller is determined using a series of one-dimensional "on line tuning" experiments; and Section V contains some numerical examples. [13]

In two sessions with free scanning and memory instructions, the eye-movement patterns of nine artists were compared to those of nine artistically untrained participants viewing 16 pictures ranging from ordinary scenes to abstraction: 12 images were created to support an object-oriented viewing mode (selection of recognizable objects) and a pictorial viewing mode (selection of more structural features), and four were abstract. The artistically untrained participants preferred to investigate human characteristics and objects, whereas the artists concentrated on structural/abstract features. A group-by-session interaction revealed that the artists changed their seeing strategy in the memory task session, viewing more objects and human traits. A verbal recall memory test revealed no overall difference in the number of photographs remembered; however, the number of correctly remembered visual aspects was significantly higher for artists than for untrained observers, regardless of picture type. There were no differences in fixation frequencies/duration across sessions. Still, a significant task-dependent group-by-session interaction of fixation frequency/duration revealed that artistically untrained participants demonstrated repetition effects in fewer, longer fixations with repeated viewing, whereas artists demonstrated the opposite pattern. [14]

Pupil sensing in a human visual video or image is useful in a variety of applications, such as eye tracking, diabetic retinopathy screening, smart homes, iris recognition, and so on. Pupil detection is hampered by a variety of issues, including light reflections, cataract disease, pupil constriction/dilation moments, contact lenses, brows, eyelashes, hair strips, and closed eye. To address these issues, the research community has been working hard to develop robust pupil localization algorithms for image/video data obtained using near-infrared (NIR) or visible spectrum (VS) illumination. This paper provides a rigorous examination of several pupil detection algorithms derived from conventional sources. This paper covers pupil localization approaches based on machine learning, histogram/thresholding, the Integro-differential operator (IDO), the Hough transform, and other techniques. The potential benefits and drawbacks of each system are addressed. Finally, this research provides advice for developing a reliable pupil detection system. This review would be an excellent resource for the related research community because the scope of pupil detection is so broad. [15]

Our primary goal is to demonstrate how light controlling cycles of the eye can cause torment or distress from glaring or visual work conditions, and how photophobia impressions can be triggered by communicating at the trigeminal core with harmful contributions from the eye. It isn't light fundamentally that is vitally causative specialist yet it is the visual light control framework working in combination with the trigeminal core that is the principal premise of aversion to light. This part broadens the properties of the model and sums up the forecasts that can be made both for photophobia and distress glare. It is proposed that cortical electrical activity is not the cause of photophobia, but rather the influence of this activity on central mechanisms as defined in the gate control theory model. It is proposed that in this case of discomfort glare and visual task work, the retinal visual cortex system is constantly seeking to optimise visual image clarity. [16]

Complexity in the human pupillary light reflex:

We investigated the dynamical characteristics of the pupillary light reflex in order to contribute to their explanation using nonlinear dynamical systems. To introduce the terminology and relevant features of the pupillary light reflex and its associated delay, we will begin with a review of human eye anatomy and physiology, with a focus on the iris, pupil, and retina. In addition, we present the most highly regarded pupil dynamics models found in the current scientific literature. This model will be defined by a nonlinear differential equation with delay, and we will present our research on the qualitative and quantitative dynamic behaviour of that neurophysiological control system. It involves functions and their derivatives, all of which occur at the same time. It is a feature that fails to consider the non-instantaneous nature of many phenomena. [17]

The human pupillary reflex (PLR complex)'s bifurcations and oscillations are investigated. Autonomous pupil area oscillations are created by electronically substituting controllable nonlinear feedback for the reflex's normal negative feedback. A theoretical framework for studying pupillary oscillations that is physiologically grounded was developed. The delay differential equation (DDE) model fits quantitatively with the simplest periodic behaviors and qualitatively with the complex ones. Much of the data's aperiodicity can be attributed to noise and transitory phenomena rather than chaos. The critical behaviour of the PLR to one oscillation differs from smooth negative feedback. The relative fluctuations of period are larger than those of amplitude in the first case. This experimental result is explained using properties of temporal solutions and densities of a stochastic ODE. This system's bifurcation delayed response by a coloured noise that is both additive and multiplicative. A theoretical overview of the behavior of stationary densities of ODEs and the origin of the carry is provided, as well as the implications for the analysis of bifurcations in neural delayed feedback systems. [18].

The time course and degree of change in the understudy region of the pupil caused by light are assessed in all vertebrate and cephalopod classes. Although the speed and extent of these reactions vary, most species, except teleost fish, exhibit broad changes in the understudy region associated with light openness. The neuron muscular pathways hidden light-evoked understudy choking are depicted and viewed as moderately preserved, albeit the exact autonomic systems contrast fairly between species. In well evolved creatures, brightening of just a single eye is known to cause tightening in the unilluminated student. Such consensual reactions occur in a wide range of indifferent creatures, and their capability and connection to decussating of the visual pathway is considered. Natural photosensitivity of the iris muscles has long been known in amphibians, but it is truly limitless in other creatures. Changes in the understudied region balance the conflicting demands of high spatial keenness and expanded responsiveness in various light levels in most species. In the few teleosts where student development occurs, they do not serve a visual function but do play a role in concealing the eye of bottom dwelling species. [20]

This paper presents a proof of concept built around a servo-controlled pan/tilt platform controlled by pupil movement for the evaluation of pupil detection-based eye-tracking algorithms. A head-mounted infrared video camera captures an image of the eye, and after detecting the center position of the pupil, its coordinates are mapped to control the pan and tilt of a miniature platform controlled by a servo motor. The system enables efficient real-world evaluation of various eye-tracking algorithms, and depending on the type of accessory mounted on the platform, it can have a wide range of application scenarios. [21]

We investigate a non-straight, time-deferred model of Pupillary Light Reflex in this paper (PLR). We consider key exhibition metrics such as dependability, assembly, and heartiness. We focus on its solidity properties and proposition rules on boundary esteems that ensure neighbourhood dependability using time and recurrence space investigation. Soundness outlines are used to investigate compromises between framework boundaries. The advantages of boundaries for which oscillatory and non-oscillatory unions occur are investigated. We demonstrate that every boundary can prompt a deficiency of solidness by using nearby Hop bifurcation. Further, the soundness of as far as possible cycles is described scientifically utilizing typical structures furthermore, the middle complex hypothesis. Bifurcation graphs go with the insightful outcomes. We lay out that the cut off cycles created are generally unsound. It reveals that when the pupillary reflex model loses its nearby dependability, it becomes difficult to control. For uncertainties in boundary values, the model's heartiness is estimated. Our work provides plan cordial rules to ensure dependability and achieve the desired level of execution and heartiness. [22]

The capability of the iris and its reaction to light in man has been of extraordinary interest to the two physiologists and nervous system specialists who needed to lay out the brain pathways engaged with the control of the student reaction, as well as to physicists also, natural designers who have frequently depicted the student light reflex (PLR) as a delightful illustration of a shut circle servomechanism. This system fundamentally could change retinal luminance with changes in encompassing light, albeit this has frequently been perceived as a valuable improvement. In expansion, numerous clinical, neuro-ophthalmological and pharmacological examinations have endeavored to lay out the convenience of the student in diagnosing sores of the visual pathways and the typical working of the retina. The frequently meandering contribution of countless brain connections in controlling the development of the iris makes the student a rich wellspring of data, in any case, it additionally guarantees that its mysteries are difficult to unwind. The presence of various uncorrelated signs in the student makes troublesome the extraction of other little signals that can reflect significant retinal and cortical handling of visual data. [23]

At the point when man attempts to discover something on a table in his grasp, he needs to measure mistake between the material and hand to play out his last reason. This implied that human manual control framework incorporates a criticism of visual framework, and is controlled by it. Obviously, albeit the manual control framework is convoluted and has various circles, servo analytic investigation of this framework has been done it might be said of robotics, As referenced over, the visual framework is one of input for human execution, while the visual framework comprises of the eyeball, eye muscles, visual cortex and association among fringe and focal device. Being constrained by this contraption, eye development should be possible easily to fulfil his will. To be specific, the visual framework, one criticism of the human manual control framework, has alleged different circle and data from the visual framework presumably proliferates to engine cortex and controls the human execution. To explain the manual control framework as far as servomechanisms, it could be viewed as that eye following control framework is a servomechanism and be sensible that the framework is considered and broke down by a technique for recurrence reaction. [24]. An original pupillary-based check framework is presented, alongside the early character confirmation results and investigation, in view of the spatio-worldly elements processed from the unconstrained pupillary motions. The creators show that this biometric quality has the capacity to give enough discriminative data to confirm the personality of a subject. Another approach to register the spatio-transient biometric format accounts of the student region changes, in a video-oculography succession under steady luminance level, is likewise presented in this paper. As indicated by the creators' information, there is no proof that different endeavours were made, addressing this system to recognize people in light of the spatio-fleeting portrayals, registered from the typical expansion withdrawal conduct of the student. In this work, aliveness will be distinguished by utilizing the data got from the unconstrained pupillary wavering instrument. [25]. The pupillary light reflex breaks down by delivering sores in afferent and efferent pathways in a progression of monkeys. One-sided enucleating and auto radiographic methods using axoplasmic stream were utilized to decide afferent pathways. Sores likewise were made in the pregeniculate core (PGN) and individual parts of the oculomotor instinctive cores. Degeneration was concentrated in Wiitanen and Nissl stained areas. Infrared pupillographic records were made during the medical procedure. Enucleation and autoradiographic studies revealed: (1) reciprocal retinal projections to the PON and PGN, and (2) predominantly lateral projections to parts of the optic plot and sub lentiform cores. [26]

The most important step in iris recognition systems is locating the iris, because all subsequent steps, such as iris normalization, feature extraction, and matching, rely on its accuracy. In an image of an eye, iris localization refers to the separation of the iris from other parts of the eye such as the pupil, sclera, eyelids, and eyelashes. This article introduces a novel method for pinpointing exact pupil location. The pupil is located by finding a point within the pupil, then the centre is obtained by using the centroid of the pupil region, and the radius for further processing is calculated from the region's binary image. The divide and conquer rule encode the student's non-circular limit. The student's circular boundary is divided into a defined number of points. These spikes are repositioned in relation to the maximum slope then together to get the exact pupil boundary. The intensity slope is used to determine the outer boundary of the iris and the eyelids. The experimental results demonstrate that the proposed iris localization method is quite effective. [27]

The iris is a profoundly precise biometric identifier. Anyway, boundless reception is ruined by the trouble of catching top notch iris pictures with insignificant client co-activity. This paper portrays an original model iris distinguishing proof framework intended for deadlock helpful access control. This framework recognizes people who stand before and face the framework after 3.2 seconds by and large. Subjects inside a catch zone are imaged with an adjusted sets of wide-field-of-view reconnaissance cameras. A subject is situated in three aspects utilizing face identification and triangulation. A zoomed close to infrared iris camera on a container slant stage is then designated to the subject. The iris camera focal point has its central distance consequently changed in view of the subject distance. Coordinated with the iris camera on the dish slant stage is a close-infrared illuminator that is made out of a variety of coordinated LEDs. Video outlines from the iris camera are handled to distinguish and fragment the iris, create a format and afterward recognize the subject. [28]

The pupil is primarily regulated by the autonomic nervous system. Recently, rhythms related to autonomic changes in heart rate and blood pressure have been observed in unconstrained Pupil Diameter (PD) changes. However, the physiological mechanisms underlying these variations have not been extensively studied. This research aims to investigate the origin of pupil fluctuations in humans by gently stimulating carotid baroreceptors using Neck Suction (NS). ECG, respiratory movement, NS pressure, and PD fluctuations were recorded from 10 normal subjects. The equipment for PD measurement and NS stimulation was developed in our laboratory. The response of the pupil to NS was studied at stimulation frequencies of 0.10 and 0.20 Hz using parametric spectral and cross-spectral analysis. In all subjects, NS rhythms were evident in the heart rate variation series at both stimulation frequencies and in the PD spectra with significant peaks (>0.5). These findings suggest that blood pressure fluctuations transmit to the pupil through carotid baroreceptor afferent pathways, although a central contribution cannot be ruled out. [29]

Spatial considerations affect saccade planning and working memory. While saccade planning and working memory are linked to attention, the effects of saccade planning are less explored in relation to working memory. Recent studies show that spatial attention interacts with local luminance in the attended area, affecting pupil size. We used local luminance adjustment to investigate the effects of saccade planning and spatial working memory. Participants were tasked with making saccades toward visual or recalled target locations, with bright and dark stimuli presented during delays. Alignment of bright stimuli with target locations resulted in more pupil constriction, especially in tasks with no interval between stimulus and target presentation, particularly in memory-delay tasks.

Sr. no	**Paper Title / Author Names / Ref no.**	**Approach/ Techniques**	**Findings/ Comments**
1.	Eyeing up the Future of the Pupillary Light Reflex in Neuro-diagnostics Hall, C. A., & Chilcott, R. P. (2018)	The pupillary light reflex shows a response when light falls on it	For bright light eye pupil is contracted and for low light, it is expanded
2.	A SERVOANALYTIC STUDY OF CONSENSUAL PUPIL REFLEX TO LIGHT Stark, L., & Sherman, P. M. (n.d.)	The human eye is considered as a control system and a reference light source is considered as input	The difference between light falling on the retina and light flux actuates the control system
3.	Stability, Oscillations, and Noise in the Human Pupil Servomechanism Stark, L. (1959)	A designed pupillometer was used for quantitative measurements in animals and human subjects with an intact central nervous system	The pupil servo shows stability with an 18db attenuation slope
4.	MODELLING AUTONOMOUS OSCILLATIONS IN THE HUMAN PUPIL LIGHT REFLEX USING NON-LINEAR DELAY-DIFFERENTIAL EQUATIONS Spitschan M., Jain S., Brainard D. H., & Aguirre G. K. (2014)	A Hopf bifurcation analysis is used to identify the criteria for instability, as well as the period and amplitude of these oscillations	It provides a generic framework for investigating the various forms of dynamical behaviors induced by the pupil light reflex

5.	Spontaneous oscillations in a nonlinear delayed-feedback shunting model of the pupil light reflex Bressloff P. C., & Wood C. v. (1998)	We study oscillation beginning in the presence of piecewise negative feedback and provide an analytical expression for oscillation time	this model describes the nonlinear features of the iris and retinal parts of the reflex circuit
6.	Design and control of a visual servomechanism for automating corneal cross-linking treatment in keratoconus patients Şahin O., & Altuɫ E. (2015)	The system includes a camera, an image processing algorithm on OpenCV sharp, a planar servomechanism system to follow the patient's eye	for automated corneal cross-linking (CCL) treatment in keratoconus patients
7.	Insight into the Transfer Function, Gain, and Oscillation Onset for the Pupil Light Reflex Using Nonlinear Delay-Differential Equations Longtin A., & Milton J. G. (1989)	DDE is demonstrated to be compatible with the measured open loop transfer function	It can be used to supplement servo control analytic methods for studying oscillations
8.	The Form of the Human Pupil Wyatt H. J. (1995)	This study was to define the pupil morphology in normal human participants	The average pupil no circularity was 0.0166 in both darkness and light
9.	Learning Eye Movement Patterns for Characterization of Perceptual Expertise	we undertake an eye-tracking experiment and gather data on eye movement	We can reveal how these subjects changed their seeing tactics during the inspection
10.	A Neural-Network-Based Approximation Method for Discrete-Time Nonlinear Servomechanism Problem Wang, D., & Huang, J. (2001)	A discrete-time nonlinear servomechanism feedback controller is based on the solution of a set of nonlinear functional equations	It outperforms the standard linear control law
11.	A Nonlinear Universal Servomechanism Ryan, E. P. (1994)	A servomechanism problem of controlling a scalar output variable to track any reference signal from some prescribed function space	The feedback is continuous
12.	Accommodation of External Disturbances in Linear Regulator and Servomechanism Problems Johnson C. D. (1971)	To create a deterministic controller that maintains set-point regulation, or servo tracking	The disturbances' action may be advantageous in achieving the primary control task
13.	Multivariable Tuning Regulators: (The Feedforward and Robust Control of a General Servomechanism Problem) Davison E. J. (1976)	The compensator identification for feedforward and robust control of a general servomechanism	Helps in examining human eye behavior
14.	Expertise in pictorial perception: (eye-movement patterns and visual memory in artists and laymen)	Eye-movement patterns from nine artists were compared to those of nine artistically untrained	There were no differences in fixation frequencies

	Vogt S., & Magnussen S. (2007)	participants viewing 16 pictures ranging from ordinary scenes to abstraction	
15.	Pupil detection schemes in the human eye Min-Allah N., Jan F., & Alrashed S. (2021)	To develop robust pupil localization algorithms for image/video data obtained using near-infrared (NIR) or visible spectrum (VS) illumination	It is important in eye-tracking, diabetic retinopathy screening, smart homes, iris recognition
16.	A model for the explanation of discomfort and pain in the eye caused by light Stone, P. T. (2009)	To exhibit how light-controlling cycles of the eye could cause torment or distress from glaring or visual work conditions	The electrical activity of the cortex is not the cause of photophobia
17.	Complexity in the human pupillary light reflex] Laureano, R. D., Mendes, D., Grácio, C., & Laureano, F. (2020)	The dynamical characteristics of the pupillary light reflex	It doesn't consider the non-instantaneous nature of many phenomena
18.	Nonlinear Oscillations, Noise, and chaos in neural delayed feedback Longtin, A. (1989)	Autonomous pupil area oscillations were produced by electronically replacing controllable nonlinear feedback for the normal negative feedback of this reflex	The critical behavior of the PLR to one oscillation is different piecewise rather than smooth negative feedback
20.	A review of their distribution, dynamics, mechanisms, and functions Douglas, R. H. (2018)	The neuron muscular pathways hidden by light-evoked understudy choking are depicted	Natural photosensitivity of the iris muscles is known in amphibian
21.	Servo Control Based on Pupil Detection Eye Tracking IEEE Electronics Packing Society., & Institute of Electrical and Electronics Engineers	It is developed for the evaluation of pupil detection-based eye-tracking algorithms, built around a servo-controlled pan	The system allows efficient real-world evaluation of different eye-tracking algorithms
22.	Stability and bifurcation analysis of a pupillary light reflex model Rajendran, J., Arutprakasam, S. S., & Warrier, A. M. (2015)	We researched a non-straight, time-deferred model of Pupillary Light Reflex	The pupillary reflex model becomes hard to control once it loses its nearby dependability
23.	Studies of basic mechanisms and clinical applications barbur, J., & Barbur, J. L. (2004)	Numerous clinical, neuro-ophthalmological, and pharmacological examinations shave endeavoured to lay out the convenience for students	Helps in cortical handling of visual data
24.	Servo analytical Study of eye tracking moment recorded by electro-oculography Iida, M. (n.d.)	The human manual control framework incorporates a criticism of the visual framework and is controlled	Proliferates to the engine cortex and controls the human execution

		by it	
25.	A new spontaneous pupillary oscillation-based verification system Villalobos-Castaldi, F. M., & Suaste-Gómez, E. (2013)	The creators show that this biometric quality can give enough discriminative data to confirm the personality of a subject	Aliveness will be distinguished by utilizing the data
26.	Anatomical analysis of pupillary reflex pathways Pierson, R. J. and M. B. Carpenter (1974)	The pupillary light reflex breaks down by delivering sores in afferent and efferent pathways in a progression of monkeys	Reciprocal retinal projections to the pretectal olivary cores (PON) and PGN
27.	Non-circular Pupil Localization in Iris Images Basit, A., Javed, M. Y., & Masood, S. (2008)	The pupil is located by finding a point in the pupil then the center is obtained using the centroid of the pupil region	The proposed method of iris localization is quite effective
28.	Stand-off iris recognition system Wheeler, F. W., et al. (2008)	Portrays an original model iris distinguishing proof framework intended for deadlock helpful access control	Recognizes people who stand before and face the framework after 3.2 seconds
29.	BARORECEPTOR-SENSITIVE FLUCTUATIONS OF HEART RATE ANDPUPIL DIAMETER Calcagnini G., Giovannelli P., Censi F., Bartolini P., & Barbaro V. (2001)	It is part realized that the student is under the control of the autonomic sensory system	The reaction of the student to the NS was learned at excitement frequencies of 0.10 and 0.20 Hz
30.	Comparing Pupil Light Response Modulation between Saccade Planning and Working Memory Wang C. A., Huang J., Yep, R., & Munoz D. P. (2018)	The mark of spatial consideration impacts has been shown through saccade arranging and working memory	The impacts were reduced when there was no possibility executed between the fix and target areas, especially in the memory-defer task

2. METHODOLGY

The purpose of this study is to design a basic control system for controlling the human pupil servo-actuator with the help of retinal light flux oscillations. Our strategy therefore is to investigate the PLR at various levels of the incident light and to deduce the changes in the size of the pupils.

Experimental Setup

- Light Source: An adjustable LED array to provide different light intensities.
- Camera System: High-speed cameras to capture real-time changes in pupil diameter.
- Data Acquisition System: Sensors and data loggers to record light intensity and pupil response.

Control System Design

The control system is designed based on the feedback mechanism of the PLR. The main components include:

- Sensors: Photodiodes to measure incident light intensity (L_REF).
- Actuators: Servomechanisms to simulate the constriction and dilation of the pupil.

- Controller: A PID controller implemented on a microcontroller (e.g., PIC) to adjust the pupil diameter based on the error signal.

Algorithm Development

We employ a digital PID control algorithm to manage the pupil's response. The algorithm's parameters are tuned to achieve optimal performance, ensuring quick and stable pupil adjustments. The control algorithm steps are:

1. Error Calculation: Determine the error as the difference between the desired light intensity (L_REF) and the actual pupil response (L_controlled).
2. PID Computation: Use the PID formula to compute the control signal.
3. Actuator Adjustment: Adjust the servomechanism based on the control signal to correct the pupil diameter.

Analytical Techniques

To analyze the system's performance, we employ several analytical techniques:

- Transfer Function Analysis: Derive the transfer function representing the delay in pupil response (transportation delay).
- Stability Analysis: Conduct linear stability analysis to determine system stability under different feedback conditions.
- Hopf Bifurcation Analysis: Examine the conditions for oscillations in pupil diameter using the Hopf bifurcation theory.

Comparison with Previous Models

Our approach builds on previous research:

- Longtin and Milton [31]: Modeled pupil dynamics under variable lighting, deriving parameters from experimental data.
- Sahin and Altug [32]: Developed a mechatronic system for automated corneal cross-linking, utilizing visual feedback for treatment efficiency.
- Stark and Sherman [33]: Conducted a servo-analysis of the light-induced pupil reflex, establishing a transfer function for the pupil. servo system.
- Bressloff and Wood [34]: Investigated spontaneous oscillations in a second-order delayed-feedback shunting model of the pupil light reflex.

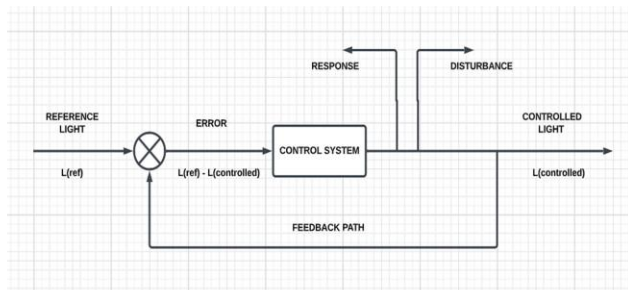

Figure 3: Block diagram for the working schematic of the proposed control system

Proposed System

In our proposed control system, the control mechanism takes into consideration the difference between the input (L_REF) and output (L_controlled) and yields a closed feedback control relationship of gain unity. This arrangement is well depicted on the system's block diagram shown earlier in figure 3.

This is expressed in our transfer function where the transportation delay also captures the response delay in terms of change in pupil diameter resulting from the presence /absence of light. While this system is capable of exerting some control over the pupil's servo functions, its usefulness is somewhat restricted when addressing the study of various eye diseases whereby in response to light, the brain is known to send out the wrong signal. Our system is designed and would be accurate for normal sighted specimens.

3. MODELLING

The transfer function governing equations are based on the Milton and Longtin model of the eye. Changes in pupil area, A, caused by imposed piecewise constant feedback can be described as follows;

$$\frac{dg}{da}\frac{da}{dt} + \propto g(A) = F(A_c) \quad (1)$$

where $\propto$ is the pupillary movement rate constant, is the neural delay, and $F(A_c)$ is a continuous piecewise function of A_c. The function $F(A_c)$ depending on whether the pupil area is greater than or less than a certain threshold. The notation A_c denotes the pupil area at one time τ in the past, i.e. $A_c = A(t - \tau)$. The feedback function, $g(A)$, changes in iris muscle activity, x, are related to changes in A, and the inverse relationship between x and A is considered.

The forcing term on the right side of (1) represents changes in retinal light flux, $\emptyset(\emptyset = IA$, where I is the retinal illumination), due to changes in pupil area. For smooth negative feedback, (1) becomes;

$$\frac{dg}{dA}.\frac{dA}{dt} + \propto g(A) = \gamma \ln\left[\frac{\emptyset_x}{\bar{\emptyset}}\right] = \gamma\left[\frac{I_r A_r}{\bar{I}\bar{A}}\right] \qquad (2)$$

where the logarithmic compression of light intensities at the retina was considered, γ is the neural firing frequency rate constant, and $\bar{I}\,\bar{A}$ are the values at the threshold.

By linearizing (2) we get;

$$\propto g(A^*) = \gamma \ln\left[\frac{I^*A^*}{\bar{I}\bar{A}}\right] \qquad (3)$$

Where A^* is the pupil area corresponding to I^*.

The linearization (2) about A^* leads to;

$$\propto^{-1}\frac{dA}{dt} + A = G.[A_c - A^*] + A^* \qquad (4)$$

Where;

$$G \equiv \frac{\gamma}{\alpha\beta A^*} \qquad (5)$$

And $\beta = \frac{dg}{dA}$ evaluated at A^*. When $\beta < 0$, As a result, G>0, corresponds to negative feedback.

The pupil light reflexes experimentally determined closed-loop transfer function;

$$H(s) = \frac{P(s)}{1+P(s)} \qquad (6)$$

where the open-loop transfer function is;

$$P(s) = \frac{G_0 \exp(-cs)}{(1+ks)^3} \qquad (7)$$

and where s denotes the Laplace variable and τ = 0.18 s. While the Bode amplitude plot's 18 db/octave roll-off suggested that the transfer function had three poles, they could not be determined individually and were all set equal to 10 s -I by selecting the time constant k=0.1 s. (derived from experimental work, Stark 1959).

The time domain form of the above transfer function is given by;

$$k^3\frac{d^3\emptyset}{dt^3} + 3k^2\frac{d^2\emptyset}{dt^2} + 3k\frac{d\emptyset}{dt} + \emptyset(t) = G_0.[F(t-\tau) - \emptyset(t-\tau)] \qquad (8)$$

3.1 State Space

The state space representation is achieved using MATLAB.

```
Tss =

  A =
           x1      x2
   x1  -11.11  -7.716
   x2       8       0

  B =
       u1
   x1   2
   x2   0

  C =
          x1     x2
   y1      0  3.858

  D =
       u1
   y1   0

Continuous-time state-space model.
```

3.2 Open loop transfer function

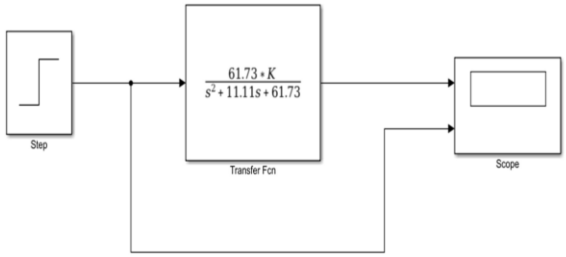

Figure 4: Open loop transfer function

3.3 Reduced transfer function

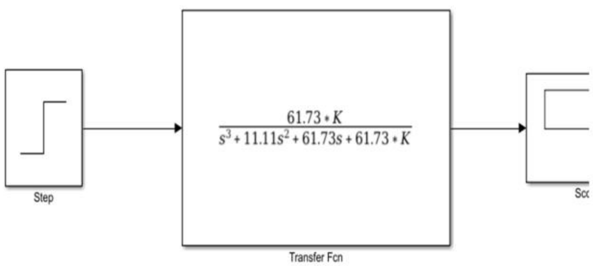

Figure 5: Reduced transfer function

4. IMPLEMENTATION AND RESULTS

The data for this project is imported from MATLAB and Simulink. Using Simulink is preferable as it has built-in commands for examining and designing control systems like step, impulse, and parabolic inputs. Other such parameters make it possible to implement our system design without designing any guide user interface. For the current scope of the project results obtained from both MATLAB and Simulink are synonymous. The graphs for responses are the same for both. In this section of the project, Simulink will be considered for tuning and designing the PID controller for this system. As our system is SISO (single input single output), we can also use MATLAB siso tool for designing stability margin and studying the effects of changing parameters on the stability of the system.

4.1 System Characteristics

The given lists all the system characteristics of our model:

Parameter	Values
Natural Frequency	7.8568
Damping Ratio	0.7070
Settling Time	0.7201
Peak Time	0.5654
%Overshoot	4.3245

For analysis purposes, the transfer function is approximated as second-order transfer with the error being less than 2%. The percentage error between our approximation and the actual transfer function is 0.5%.

4.2 Response Comparison

The tep response comparison is given in the following figure;

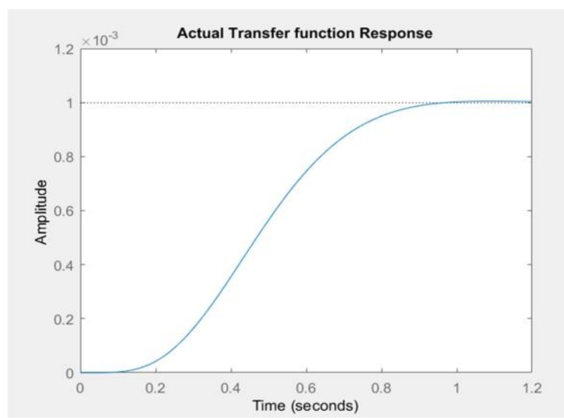

Figure 6: Actual step response

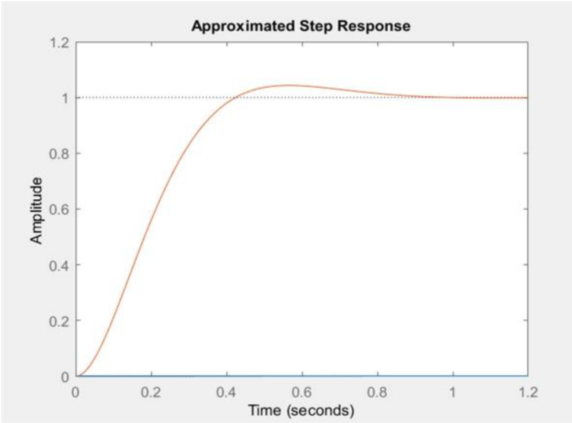

Figure 7: Approximated step response

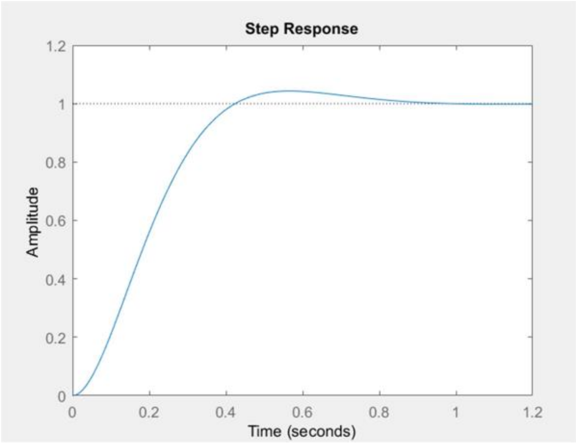

Figure 8: Step input resonance

Our system is quite stable as it has minimal overshoot and no oscillations. Considering the current response of our system, it shows near-ideal behavior for step responses. Our applications suggest inputs are in the form of single-step inputs and single outputs with certain transportation delays. Transportation delays are case-sensitive for individuals.

4.3 Ramp Input

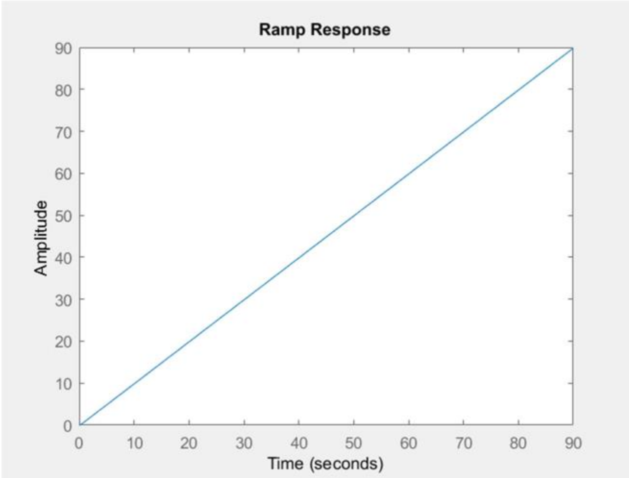

Figure 9: Ramp input response

For ramp input, our system shows instability. It is best suited to cater to step input operations.

4.4 Parabolic Input

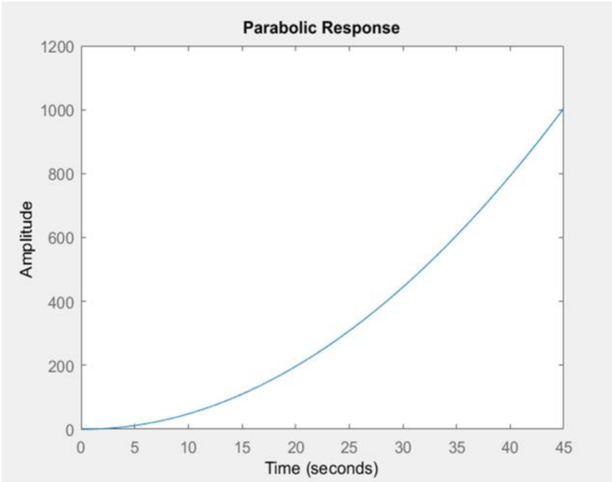

Figure 10: Parabolic input response

For parabolic input, we get an increasing slope towards infinity that shows that the system becomes unstable under parabolic inputs.

4.5 Stability and Gain Limits

The pole-zero plot from MATLAB shows two poles in the left half plane. So, our system is a table. At K=1 the poles stand between -5 and -6 points on the real axis so we can try to shift our plots toward the right to choose between sluggishness and controllability of the system.

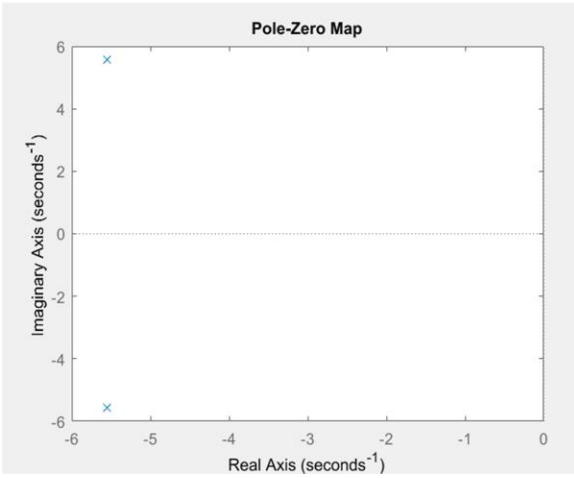

Figure 11: Pole-Zero Plot

Using MATLAB, we get the gain limits of the P controller as 0<K<12. So, the system is stable for values between 0 and 12 of the real axes.

The following code is used in MATLAB to find out the position constant, velocity constant, and acceleration constant with associated steady-state errors.

```
%main code
num = [61.73];
den = [1 11.11 61.73];
TF = tf(num,den);
step(TF)
stepresults = stepinfo(TF)
%STEP INPUT
kp = dcgain(TF)
essstep = 1/(1+kp)
%RAMP
numsg = conv([1 0],num);
%densg = [1 11.11 61.73];
densg = den;
sG = tf(numsg,densg);
sG = minreal(sG);
kv = dcgain(sG)
essramp = 1/kv
%PARABOLIC
nums2g = conv([1 0 0],num);
%dens2g = [1 11.11 61.73];
dens2g = den;
s2G = tf(nums2g,dens2g);
s2G = minreal(s2G);
ka = dcgain(s2G)
essparabolic = 1/ka
```

```
kp =

     1

essstep =

    0.5000

kv =

     0

essramp =

   Inf

ka =

     0

essparabolic =

   Inf
```

As the system under study is a 0-type system it has no poles on the origin so must show infinite steady-state error for ramp and parabolic inputs while having a constant steady-state error for step input.

4.6 Root Locus

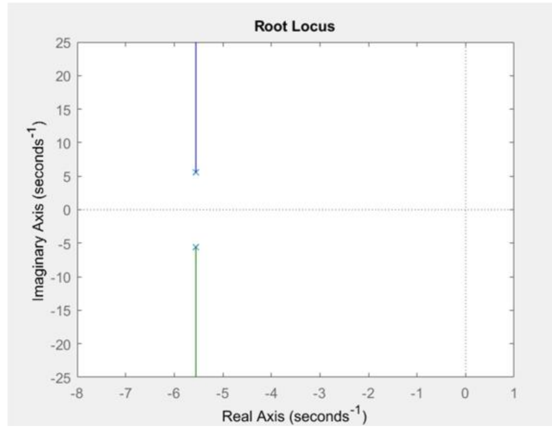

Figure 12: Root locus plot

Root locus shows locus starts from two points in the left half plane and ends at infinity as the system has no zeros.

4.7 PID controller:

The tuned PID response is shown which shows minimal overshoot and steady state error. So, the system is ideally tuned for step inputs. The current operational boundaries do not require the use of a ramp or parabolic input so, the system is sufficient enough in terms of stability and controllability for servo analytic control of the human eye pupil.

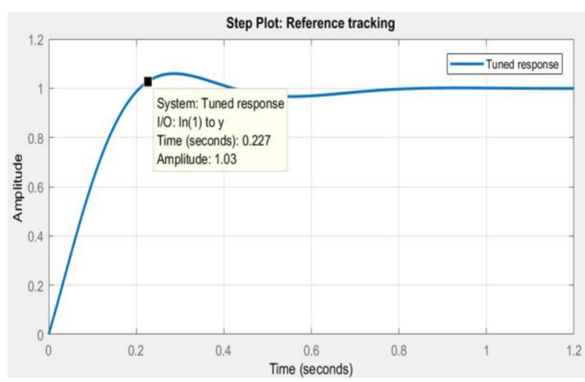

Figure 13: PID Response

The control parameters are represented in the table below:

Parameter	Gain values

Ki	2.1459
Kp	11.7334
Kd	0.098113

The tuned gains are minimal so in terms of cost the PID tuner is sufficient and desirable.

4.8 Discussion

In our project, we aimed to model and control the human pupil's response to light using a servomechanism approach. Our results are derived from simulations and analysis conducted using MATLAB and Simulink. The following outlines the key findings and their implications.

System Characteristics

The natural frequency of our system was found to be 7.8568, with a damping ratio of 0.7070. These values indicate a well-damped system, which is crucial for minimizing oscillations and ensuring stability. The settling time was calculated to be 0.7201 seconds, and the peak time was 0.5654 seconds. The percentage overshoot was relatively low at 4.3245%, indicating that the system is stable and does not exhibit excessive oscillatory behavior.

Step Response

The step response of the system was analyzed to determine its stability and performance. The actual step response showed minimal overshoot and no oscillations, demonstrating near-ideal behavior for step inputs. This stability is essential for accurately controlling the pupil's response to sudden changes in light intensity.

Ramp and Parabolic Inputs

For ramp inputs, the system exhibited instability, indicating that it is best suited for step input operations rather than gradual changes. Similarly, the response to parabolic inputs showed an increasing slope toward infinity, further confirming the system's instability under these conditions. These findings suggest that while the system performs well with sudden changes in light intensity, it may not handle gradual changes as effectively.

Root Locus and Pole-Zero Plot

The root locus plot revealed that the system's poles are located in the left half of the complex plane, confirming its stability. The pole-zero plot further supported this, showing that the poles are positioned between -5 and -6 on the real axis. This placement ensures that the system remains stable for a range of gain values.

PID Controller Tuning

To enhance the system's performance, a PID controller was implemented and tuned. The tuned gains were Ki = 2.1459, Kp = 11.7334, and Kd = 0.098113. The PID response showed minimal overshoot and steady-state error, indicating that the system is well-tuned for controlling the pupil's response to light. The tuned PID controller effectively balances stability and responsiveness, making it suitable for practical applications in controlling the eye's servomechanism.

5. CONCLUSIONS

Our objective was to design a control system for controlling the human eye pupil response. This could be achieved through a number of approaches, in our approach a light source is used to control the pupil size (its diameter) and a camera for capturing the change in its size. The data from the camera is used to account for transportation delay in eye response. The shift in pupil size is then utilized to generate a light function. The desired response of the pupil is then incorporated into a function of light. A data set obtained from experimentation will specify a light reading for a particular pupil diameter. In this way, input and output can be interpreted as a function of light. Alternatively, the incident light can also be interpreted as a function of the diameter change of the pupil (its size). A higher resolution camera will provide a more comprehensive data set of what type of light intensity produces what type of change in diameter. In the case of light as an input and output function, the feedback mechanism while accounting for transportation delay will vary light intensity to obtain a particular change in pupil size. The modeling results demonstrate that our control system can accurately predict and control the human pupil's response to light with high stability and minimal overshoot. The system's performance is optimal for step inputs, showing instability under the ramp and parabolic inputs, indicating it handles sudden changes in light intensity better than gradual ones. The PID controller tuning with gains Ki = 2.1459, Kp = 11.7334, and Kd = 0.098113 ensures the system's stability and responsiveness. These results suggest that our control system is a reliable and practical tool for studying and managing the eye's servomechanism. This system has significant potential for applications in medical research and the treatment of vision-related conditions, providing a foundation for advancements in ophthalmology.

6. RECOMMENDATIONS

In the future instead of deriving a generic system for all sorts of specimens, a dynamic system should be devised that could incorporate different time delays and can obtain a data set for inputs and outputs specific to a person. The suggested system should work in phases; the first phase is for developing a data set for light-diameter relationship innate to a particular person under study, in the second phase the system should be checked. All these steps should be made possible to occur as fast as possible for a better practicality factor.

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