AUTONOMOUS FOOSBALL TABLE

PATTERNS IN IPV6 ADOPTION

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Computer Engineering

By
Aidan Himley

October 27, 2022

Technical Team Members:
Hudson Burke
Coleman Jenkins
James Long
Zachary Yahn

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Rider Foley, Department of Engineering and Society

Harry Powell, Department of Electrical and Computer Engineering

INTRODUCTION

The use of robots to perform human tasks is a rapidly developing field. Many human jobs have been replaced with automation already in the manufacturing industry, and as costs of automation fall, demand for it will continue to grow (Tilley, 2017). In addition to robots that have direct practical use by performing repetitive manufacturing tasks, even robots that perform purely recreational tasks have real-world importance. The task of designing, building, and programming robots in any application domain helps educate engineers in the field of robotics, which has important implications for manufacturing as the increase of robotics education is a major factor behind the growth of automation in the industry (Tilley). In addition, robots that seek to perform a quintessentially human, recreational task can reveal challenges that are easy for humans, but difficult for robots. These challenges give insight into the limitations of current robotic and computing techniques, and occasionally produce novel techniques inspired by those found in humans or nature. For example, during the construction of a robotic foosball table, a team at Western Sydney University used a novel type of sensor inspired by the human eye to detect the ball, a task which is easy for humans, but requires intense computational resources with traditional robotics techniques (Cohen, 2022).

As a microcosm of the endeavor to replace human tasks with automation, my capstone team will pursue the design and construction of a robotic foosball table. We intend to build a table with one team operated robotically so that a human can play against it, with the goal of achieving performance that exceeds that of a human player.

TECHNICAL TOPIC

The primary challenges to achieving human-like foosball performance are quickly and reliably detecting the position of the ball and actuating the physical rods with enough speed and precision to respond. Given the speed at which a human player can shoot a ball, there is only a tiny fraction of a second to detect the ball and respond appropriately, straining the bounds of computation and acceleration. In addition, the needs of traditional image processing methods that operate on a grid of pixels at a set frequency can quickly overwhelm computational resources, as the amount of data to be processed grows rapidly with the frequency and resolution of the camera. Obstruction of the ball from view by the rods and players of the table adds another challenge to ball recognition for an optical detection system.

Several groups have tackled these challenges before and built robotic foosball tables of their own. A team at École Polytechnique Fédérale de Lausanne in Switzerland solved the obstruction problem by replacing the floor of the table with clear acrylic and used a camera with a very high framerate of 300 fps to track the ball quickly enough (École Polytechnique Fédérale de Lausanne, 2013). A team at Brigham Young University used a similar system, but with an unmodified table surface and an overhead camera (Hollingshead, 2016). A team of students at Indiana University created only a ball detection system (no physical actuation) and also used an ordinary camera, but had to decrease the resolution to 240 vertical pixels and the framerate to 30 fps in order to reduce the amount of data for the computation (Bambach & Lee, 2012). Most uniquely, a team at Western Sydney University created a solution that tackled the computation problem by using a “neuromorphic vision sensor” rather than an ordinary camera. This sensor specifically tracks changes in an image, similar to a human eye, which greatly reduces the amount of data to be processed (Cohen, 2022).

The approach chosen by my group is ultimately driven by the constraints imposed by our available time and budget of one semester of work and 500 dollars. In light of these constraints, we will use the miniature foosball table shown in Figure 1, rather than a full-size table, to reduce the intensity of the computation and acceleration required.

Figure 1: The miniature foosball table (Himley, 2022)

The $500 budget limits the ball detection system to the use of an ordinary camera rather than more expensive sensors that produce less data. To process the data from the camera, we use a very simple algorithm that compares each pixel independently to a target color, calibrated to the color of the ball. Based on the difference between the pixel color and target color, each pixel is assigned a single value that indicates how similar it is to the target color, producing the image shown in Figure 2, where brighter pixels are more similar to the target color. The similarity values are compared to a threshold value to determine which pixels make up the ball, then the mean x and y coordinates of all the ball pixels are calculated to find the center of the ball.

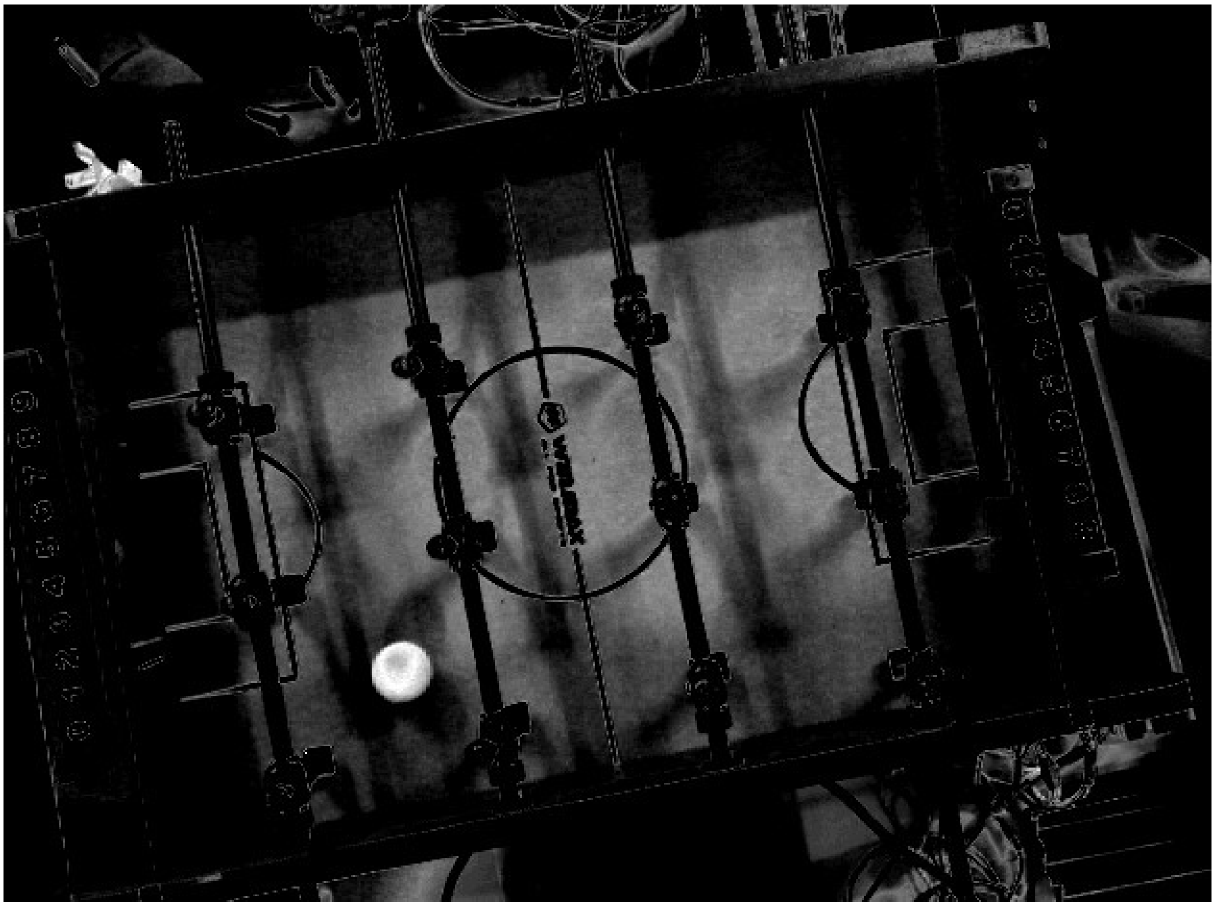

Figure 2: Image of the foosball table after per-pixel similarity function (Himley, 2022)

To actuate the foosball players, we will use Direct Current (DC) brush motors; for each rod controlled by the robot, we use one motor to move the rod linearly and one to rotate the players and kick the ball. As shown in Figure 3, the motor responsible for linear actuation drives a 3D-printed mount along a belt and gantry system. This mount holds the motor responsible for rotational motion, which in turn connects directly to the table rod by a 3D-printed shaft coupling. The motors for linear motion are rated for a speed of 1600 revolutions per minute (RPM) and torque of 3.0 kg·cm, allowing the robot to move the rod from one end of the table to the other in 0.3 seconds. The motors for rotational motion are rated for a speed of 450 RPM and torque of 2.4 kg·cm, allowing the robot to kick the ball at 1.3 meters per second.

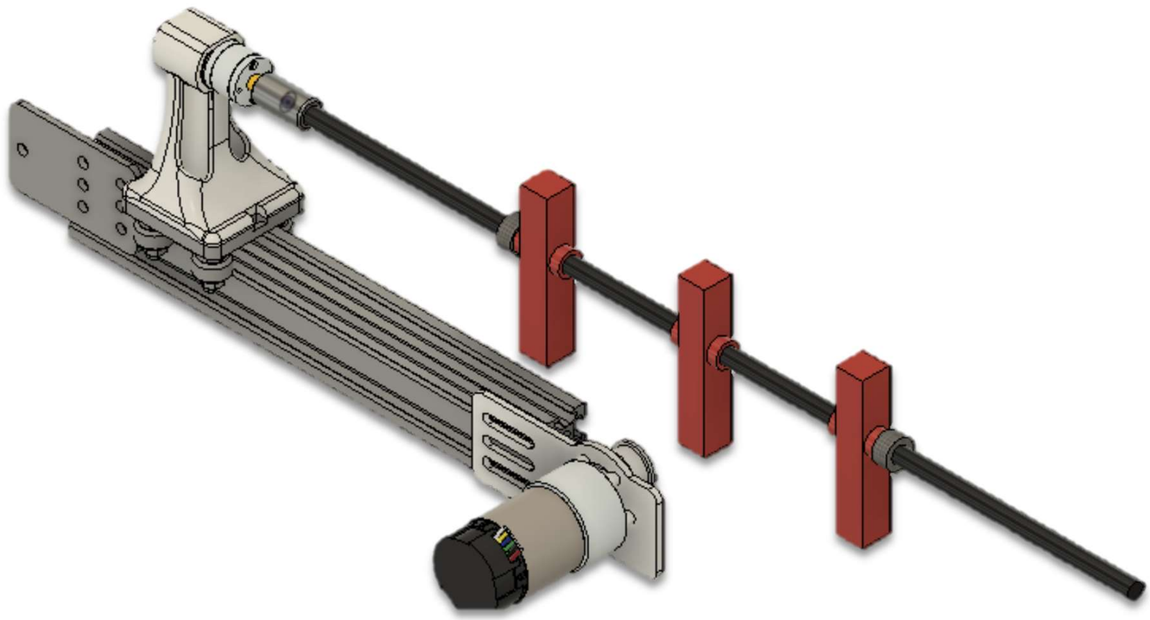

Figure 3: CAD drawing of the motor assembly (Himley, 2022)

NEXT GENERATION INTERNET

Internet Protocol version 4 (IPv4) supports about 4 billion addresses, which computers use to uniquely identify the sender and recipient of a message over the internet (IETF, 1981). By the late 20th century, it became clear that 4 billion addresses would not be enough, as the explosion in the number of internet-connected devices would eventually exhaust the space of all possible addresses. To combat the coming problem, Internet Protocol version 6 (IPv6) was created, with support for more than 340 undecillion addresses, far more than will ever be needed as long as internet-connected devices are limited to one planet (Hinden & Deering, 1998).

Although the IPv6 standard has existed since 1998, adoption of the new protocol had been slow well into the 2010s (Fruhlinger, 2022). During this time period, the predicted exhaustion of IPv4 addresses has come to pass in phases – first at the root-level allocation pool held by the Internet Assigned Numbers Authority in 2011, then at various dates from 2011 to 2015 for the Regional Internet Registries, which assign addresses to customers for use (Huston, 2022). Despite address exhaustion becoming a reality, IPv4 remained the dominant protocol in use, as new technologies have extended its useful life, even in the face of address exhaustion.

However, in recent years IPv6 adoption has accelerated significantly. Researchers in 2014 noticed that adoption, while still low, was beginning to show signs of acceleration and should be execpected to become dominant in the next few years (Czyz et al., 2014). The acceleration continued, and at the present day, about 40% of all Google traffic takes place over IPv6 (Google, 2022). In 2020, the United States Office of Management and Budget even issued a mandate for IPv6 deployment on federal government projects, including aggressive near-term goals such as 80% adoption by 2025 (Vought, 2020). As motivation, the mandate cites decreasing technical and economic viability of IPv4, as well as industry trends towards full IPv6 adoption. In this paper, I will investigate the social and technical forces behind the recent acceleration of IPv6 adoption.

In his article "The Evolution of Large Technological Systems," Thomas Hughes provides an analytical framework that can be used to understand the historical patterns of IPv6 adoption. Hughes describes sociotechnical system evolution as a sequence of phases from an initial technological invention, through development and innovation to a system that is viable economically and compatible with other existing systems through transfer, growth, competition, and consolidation as the system continues to evolve (Bijker et al., 2012). Of particular interest to my analysis is the development phase, in which an invention that initially can only function in simple test environments must grapple with the complex technical, social, and economic forces of the real world in which it must exist. If successfully developed, a technology is socially constructed as each real-world factor adds to its requirements and capabilities until the invention becomes a technological system.

Much of the acceleration in IPv6 adoption is due to development of the protocol from the original standard to a system that can work in the real world and interoperate with existing systems. For example, in T-Mobile's transition to an IPv6-only internal network, T-Mobile identifies a specific development called 464XLAT as the deciding factor that enabled the transition (T-Mobile, 2014). 464XLAT is a transition technology that helps computers using IPv6 and IPv4 communicate, which T-Mobile argued worked more effectively than previous transition technologies available at the time. Thus, 464XLAT helped develop IPv6 into a system that both can function with existing technological systems and meet the needs of T-Mobile as an organization.

Hughes also defines the concept of technological momentum, the tendency of a large technological system to resist sudden change. He identifies physical capital, collective knowledge of a community of practitioners, regulatory bodies, and organizational investment of firms and investors in the success of a system as major contributors to momentum, all of which tend to accrue as a system grows (Bijker et al., 2012). A 2008 paper on adoption of IPv6 in the North American region offers a method of quantifying the momentum held by IPv4 and its implications for IPv6 adoption (Elmore et al., 2008). Using data on IPv6 adoption up to that point and a mathematical model of diffusion in which adoption is slow at first, then accelerates with the number of adopters as knowledge of the new technology grows, the paper finds that

IPv6 adoption would not be widespread before the exhaustion of IPv4 addresses came to pass. It also identifies organizational investment in IPv4 networks and a personal desire of engineers to keep their skills relevant as significant contributors to the slow growth of IPv6, two concepts which Hughes also identifies as contributors to technological momentum.

To understand why IPv4's high amount of momentum has increasingly been overcome, we can leverage Hughes' concept of reverse salients, which he describes as elements of a technological system that lag behind the rest of the system and degrade its performance, requiring engineers to remedy them in order to maintain the health of the system. In these terms, exhaustion of IPv4 addresses can be considered a reverse salient as it inhibits the growth of computer networks. However, while IPv4 address exhaustion was long predicted, it only became a reverse salient once it actually came to pass and began to affect organizations. For example, Facebook only transitioned their internal network to IPv6 in 2014 because the growth of their network outpaced the capabilities of the technology they had been using to remain using IPv4 (Facebook, 2014). This suggests a model of IPv6 adoption where diffusion alone is not sufficient to overcome the momentum of IPv4 until address exhaustion forms a reverse salient and forces engineers to transition to IPv6 to preserve the health of their systems.

RESEARCH QUESTION AND METHODS

To further my understanding of IPv6 adoption, I intend to investigate the following research question: What social and technological factors have contributed to the acceleration of IPv6 adoption in the last decade, and what factors are still holding it back? This question is important to the future health of the internet, which supports entire industries and touches the daily lives of people across the world. As the internet continues to grow, the long-term solution to providing addresses for new devices will continue to increase in relevance.

To answer this question, I will gather data from company reports in the tech industry related to individual firms' transitions to IPv6, as well as media accounts of those transitions. As the overall transition of the internet in general to IPv6 is the sum of many individual decisions, I hope to examine those individual decisions in order to gain an understanding of the system as a whole. I will also gather data from prior literature on IPv6 adoption from multiple points in time between now and 1998.

To analyze the data gathered, I will treat individual company reports as case studies to understand the complex real-world factors involved in the IPv6 transition and how IPv6 interacts with the world as a technological system. I will compare perspectives from different time periods to understand how IPv6 as a system and perspectives regarding it have changed over time. Finally, I will synthesize my findings using Hughes' framework of evolution of technological systems.

CONCLUSION

My technical deliverable is the design and construction of a robotic foosball table with which a human player can compete against an autonomous opponent. I expect this project to provide insights into the aspects of human tasks that current automation methods struggle to perform and how those challenges can be overcome. My STS deliverable is a paper researching the factors contributing to historical acceleration of IPv6 adoption its current trajectory. I expect this research to provide insight into why IPv6 adoption has taken the path it has, which is an important topic to the health of the internet as the number of internet-connected devices continues to grow.

REFERENCES

Bambach, S., & Lee, S. (2012). *Real-time foosball game state tracking*. Tech. rep., School of Informatics and ComputingIndiana University.

Bijker, W. E., Hughes, T. P., & Pinch, T. (Eds.). (2012). *The social construction of technological systems: New directions in the sociology and history of technology* (Anniversary ed). Cambridge, Mass: MIT Press.

Cohen, G. (2022, February 27). Why We Built a Neuromorphic Robot to Play Foosball. Retrieved October 27, 2022, from IEEE Spectrum website: https://spectrum.ieee.org/robotic-foosball-table

Czyz, J., Allman, M., Zhang, J., Iekel-Johnson, S., Osterweil, E., & Bailey, M. (2014). Measuring IPv6 adoption. *Proceedings of the 2014 ACM Conference on SIGCOMM*, 87–98. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/2619239.2626295

École Polytechnique Fédérale de Lausanne. (2013). A Robot to Beat Humans at Foosball. Retrieved October 27, 2022, from https://cacm.acm.org/news/167371-a-robot-to-beat-humans-at-foosball/fulltext

Elmore, H., Stephens, B., & Camp, L. J. (2008, August 25). *Diffusion and Adoption of IPv6 in the Arin Region* [SSRN Scholarly Paper]. Rochester, NY. https://doi.org/10.2139/ssrn.1255262

Facebook. (2014, June 6). Case Study: Facebook Moving To An IPv6-Only Internal Network. Retrieved October 16, 2022, from Internet Society website: https://www.internetsociety.org/resources/deploy360/2014/case-study-facebook-moving-to-an-ipv6-only-internal-network/

Fruhlinger, J. (2022). What is IPv6, and why is adoption taking so long?: IPv6 has been in the works since 1998 to address the shortfall of IP addresses available under Ipv4, yet despite its efficiency and security advantages, adoption is still slow. *Network World (Online)*. Retrieved from https://www.proquest.com/advancedtechaerospace/docview/2641602055/abstract/86230BC3276E4CB2PQ/13

Google. (2022). IPv6 – Google. Retrieved October 15, 2022, from https://www.google.com/intl/en/ipv6/statistics.html

Hinden, B., & Deering, S. E. (1998). *Internet Protocol, Version 6 (IPv6) Specification* (Request for Comments No. RFC 2460). Internet Engineering Task Force (IETF). https://doi.org/10.17487/RFC2460

Hollingshead, T. (2016, April 25). BYU-created A.I.-powered foosball table goes head to head with humans. Retrieved October 27, 2022, from News website: https://news.byu.edu/news/byu-created-ai-powered-foosball-table-goes-head-head-humans

Huston, G. (2022, October 16). IPv4 Address Report. Retrieved October 16, 2022, from https://ipv4.potaroo.net/

Internet Engineering Task Force (IETF). (1981). *Internet Protocol* (Request for Comments No. RFC 791). https://doi.org/10.17487/RFC0791

Tilley, J. (2017). Automation, robotics, and the factory of the future | McKinsey. Retrieved October 27, 2022, from https://www.mckinsey.com/capabilities/operations/our-insights/automation-robotics-and-the-factory-of-the-future

T-Mobile. (2014, June 13). Case Study: T-Mobile US Goes IPv6-only Using 464XLAT. Retrieved October 16, 2022, from Internet Society website: https://www.internetsociety.org/resources/deploy360/2014/case-study-t-mobile-us-goes-ipv6-only-using-464xlat/

Vought, R. T. (2020, November 19). *Completing the Transition to Internet Protocol Version 6 (IPv6)*. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2020/11/M-21-07.pdf