Design and Development of Kinematic Models Using 3D Printing and Integration of IOT Systems

M. Sanjay Nag[1] | B. SaiVinay[2] | P. Sahadev[3] | K. Joshan Kumar[4] | V. Ananda Babu[5]
[1,2,3,4]Students of Mechanical Engineering Department, Nadimpalli Satyanarayana Raju Institute of Technology, (NSRIT), Autonomous, Visakhapatnam – 531173.
[5]Associate Professor, Department of Mechanical Engineering, Nadimpalli Satyanarayana Raju Institute of Technology, (NSRIT), Autonomous, Visakhapatnam – 531173.

Abstract: The development of rapid prototyping and intelligent systems has revolutionized mechanical design and automation. This paper presents the design and development of kinematic models using 3D printing technology with the integration of Internet of Things (IoT) to provide dynamic motion, monitoring, and control. The project is aimed to design and develop the kinematic models of mechanical power transmission systems such as linkages and gears using additive manufacturing technology. The models are integrated with IoT-based microcontrollers for real-time control and visualize the motion of kinematic mechanisms. The integration of 3D printing and IoT provides a platform to understand and enhance the knowledge in diversified technologies which play a key role in engineering education for both teaching fraternity and students community to develop smart power transmission systems. The kinematic models developed using 3D printing technology describe the more responsive in motion, customizable in scaling and integration with IoT allows for the creation of systems that can be easily adapted for different real time applications.

Keywords: 3D Printing, Kinematic Models, IoT Integration, Rapid Prototyping, Additive Manufacturing, Mechanical Design, Smart Systems, Remote Monitoring, Automation, Real-Time Control.

I. INTRODUCTION

The engineering design revolution has been most profoundly influenced by the integration of smart systems and digital manufacturing. Among all the new technologies, 3D printing or additive manufacturing is one such revolutionary technology that has allowed us to design cheaply and rapidly complex mechanical components. Meanwhile, the Internet of Things (IoT) has also facilitated things, allowing devices to communicate, sense, and connect, reorganizing new fields of automation and intelligent control.
Kinematic models—mechanical models that simulate motion through linkages, joints, and actuators—are the foundation of mechanical and robotics engineering. They have, in the past, been employed in education, motion analysis, and prototype testing. With the addition of IoT technologies, the character of the models shifts by adding real-time monitoring, data logging, and remote control. This article describes the production and manufacture of such kinematic models through 3D printing methods, and IoT systems to create an interactive smart platform. Low-cost microcontrollers, sensors, and wireless communication modules are utilized to create models as dynamic research and education tools. Integration is to close the gap between theoretical mechanical theory and actual smart, modern applications.

The use of physical models in engineering has had, until the last quarter century, a long and useful history. This is especially true in machine design and engineering. Filippo Brunelleschi (1377-1436), the architect and engineer of the Duomo in Florence is known to have created construction models, including machines. In later centuries Christopher Polhem (1661-1751) in Sweden created a ‘mechanical alphabet’ of models for machines. Robert Willis (1800-1875) of Cambridge was also known for his kinematic teaching models though few have survived. Franz Reuleaux (1829-1905) of

Berlin created the world's largest collection of kinematic models at the Technical University of Berlin with over 800 models [6].

II. DESIGN AND DEVELOPMENT OF MECHANISMS

Using 3D printing technology for designing and constructing kinematic models has advanced mechanical design and automation to a great extent. It provides a method by which complex mechanical elements like linkages and gears are developed so easily with such precision and efficiency. With additive manufacturing being versatile, it is simple to rapidly prototype and customize such models, providing avenues for applying the same in research, for teaching purposes, and for real-time applications. This development provides possibilities in utilizing the application of kinematic modeling along with the application of 3D printing technology in designing high-level mechanical systems.

For instance, research on precision forward design for 3D printing utilizes kinematic sensitivity via the Jacobian matrix to account for uncertainties in the manufacturing process, aiming to improve the precision of printed components [1]. Additionally, the development of novel 3D printer robotic systems with multiple degrees of freedom has been explored to enhance the capabilities of 3D printing in producing complex kinematic structures [2].

Furthermore, the application of kinematic analysis in 3D printing mechanisms has been investigated to optimize the movement and accuracy of print heads, which is crucial for achieving high-quality prints [3]. The use of kinematic models extends beyond traditional mechanical components; for example, the creation of dynamic objects with embedded kinetic energy has been demonstrated, allowing for the 3D printing of self-propelled mechanisms [4].

In general, fabricating flexible structures requires advanced fabrication devices or involves design processes that are too complex and challenging for novice users Researchers have developed interactive design tools to help novices fabricate flexible structures using certain mechanisms: Ondulé and Kinergy allow beginners to create helical springs within 3D models for kinetic motions and energy, which are printable with FDM printers. Mechanism Preboard combines an augmented reality system to help users design and fabricate linkage mechanisms. We have developed a design tool to help users quickly create a G-code file of folded models, which is auto-generated from imported 3D models, and ready to be 3D printed [5].

III. 3D PRINTNG OF KINEMATIC MODELS

3D printing of kinematic models has been of great utility in mechanical design, prototyping, and education. The models simulate mechanical motion through linkages, gears, cams, and joints and are thus central to kinematic system studies of machinery and robotics. Additive manufacturing enables quick and cheap production of the models, frequently allowing complex geometries and interlocking parts to be produced in a single print without assembly. Design considerations in the process primarily ensuring adequate clearances for moving parts, reducing support structure, and choose suitable materials with strength, flexibility, or toughness depending on the model's function.

Besides exporting these models as drawings, rendered 3D images and animations, they may be exported for printing on rapid-prototyping fabricator as a file in STL format. This file describes the surfaces of the object as a tessellation of triangles. There are several rapid prototyping technologies, including laminated object manufacturing (LOM), selective laser sintering (SLS), photo polymerization (stereolithography, SLA), and fused deposition modeling (FDM). The FDM process was used in this study to reproduce several Reuleaux-Voigt kinematic models [6].

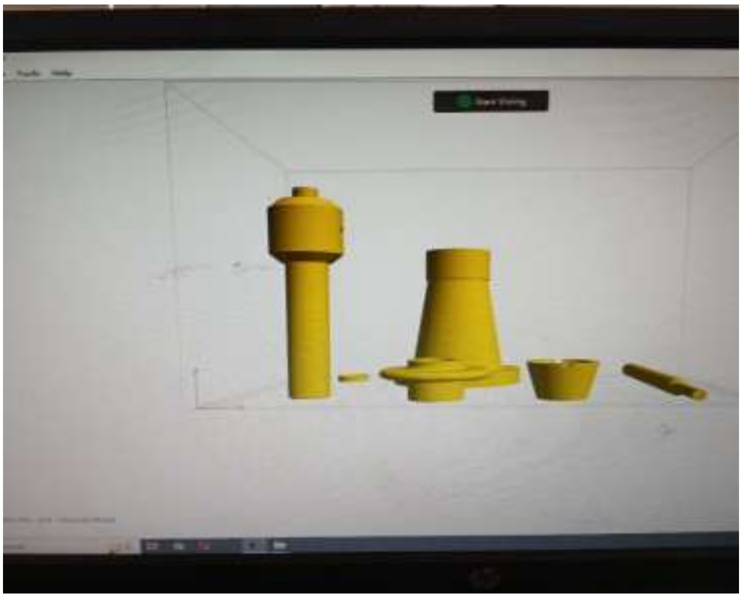
IV. DEVELOPMENT OF LEVEL-1 MECHANISMS

1. KNUCKLE JOINT

A knuckle joint is a strong but simple mechanical joint used to connect two members or rods to allow them to carry tensile loads and provide some angular movement in one direction. It consists of one eye (rod with a hole), a fork and double eye and a knuckle pin that retains them together, typically retained by a cotter pin or a collar for support. Constructed from metal like steel or aluminum, the joint is valued as being sturdy, easy to build, and adaptable. Knuckle joints are used extensively in automobile steering and suspension systems, machinery like engines and robot arms, structural applications like bridges and cranes, watch chain and bicycle linkages, heavy vehicle applications like tractors, and even windshield wiper drives, and hence are of utmost importance in applications requiring durability and controlled motion**.** For instance, modeling and analysis performed using Solid Edge and ANSYS Workbench have provided accurate solutions for evaluating the performance of knuckle joints under various load conditions. This approach ensures that the joints can withstand operational stresses without failure [7].

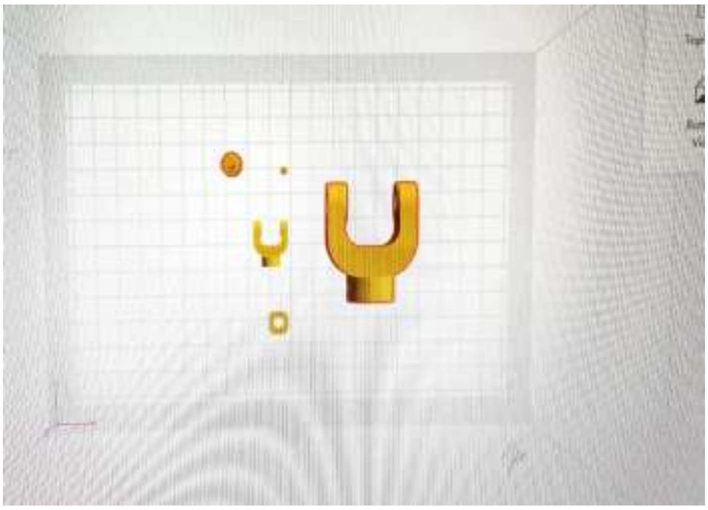
2. SCREW JACK

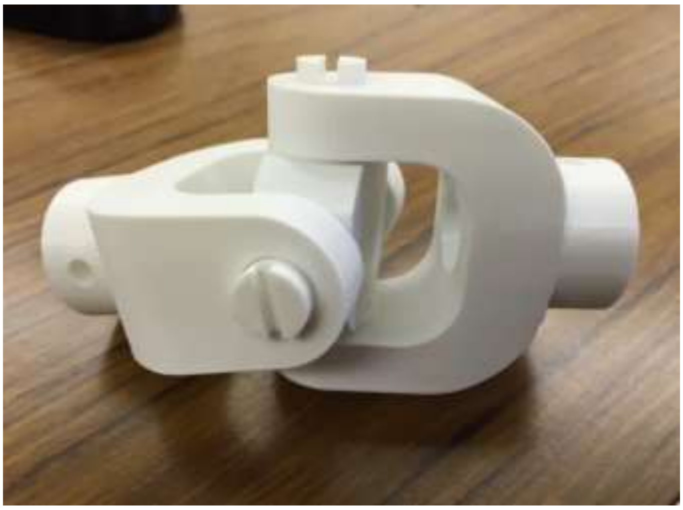
Screw jack is a machinery of lifting that is founded on the screw thread principle for converting rotating torque into linear torque, through which it can raise, lower, or suspend heavy weights with less force. Its major components consist of a screw thread, load-bearing platform or saddle, and base housing. When the screw is turned, either by hand with a handle or by motor, the platform is moved upward or downward depending on the direction of turn. The mechanical advantage allows even very heavy loads to be lifted with relatively little effort. Screw jacks are frequently used in motor vehicle service to lift cars in repair or maintenance operations. Screw jacks find application in industry, construction works, and mechanical workshops where heavy parts are to be lifted or aligned with precision. Screw jack has one of the largest advantages that it is able to withstand a load without constant power due to the nut-screw friction. This makes it not only efficient but also safe to use for an extended duration of time. Apart from lifting, screw jacks utilized in such things as altering the height of stages, bracing structural members, and even utilized in stage equipment to move scenery up or down.



3. UNIVERSAL COUPLING

A universal coupling or universal joint (U-joint) is a mechanical union to connect two shafts which are not straight line aligned in order to pass the rotational movement and torque but at the same time possess a provision to take in angular misalignment. A universal coupling is generally constructed as a cross-member item with four arms with bearings lying between two bolted-to-shafts yokes. The joint is bent in any direction for the design to accommodate up to 30 degrees or more angles, depending on design. Universal couplings are valued for compactness, versatility, and capacity to deliver constant power in the case of misalignment. Universal couplings find applications in wide uses in car drives, for example, to join the driveshaft to the differential of rear-wheel-drive vehicles for delivering smooth power to the wheels. Universal couplings connect rotating components in machinery, including pumps, conveyors, and heavy equipment like cranes. Universal joints are utilized in farm tractors and harvesters in power take-off (PTO) drives. Universal couplings are used in marine propeller shafts, aircraft control systems, and medical equipment that require transmitting accurate motion. Universal joints are easy to use but must be serviced at regular intervals in order to prevent wear, therefore providing consistent performance in most uses.

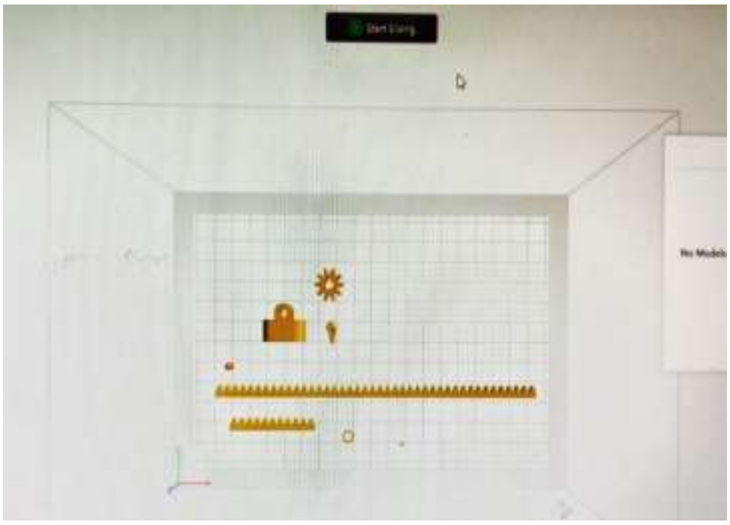


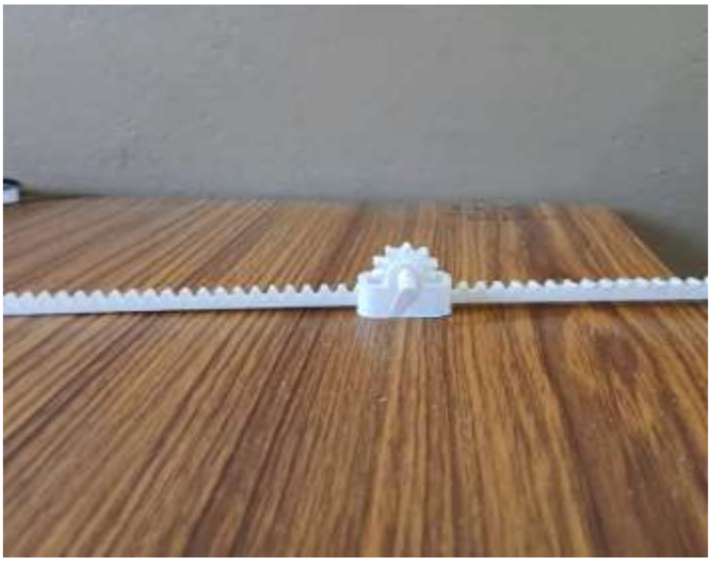


V. DEVELOPMENT OF LEVEL-2 MECHANISMS

1. RACK AND PINION GEAR MECHANISM

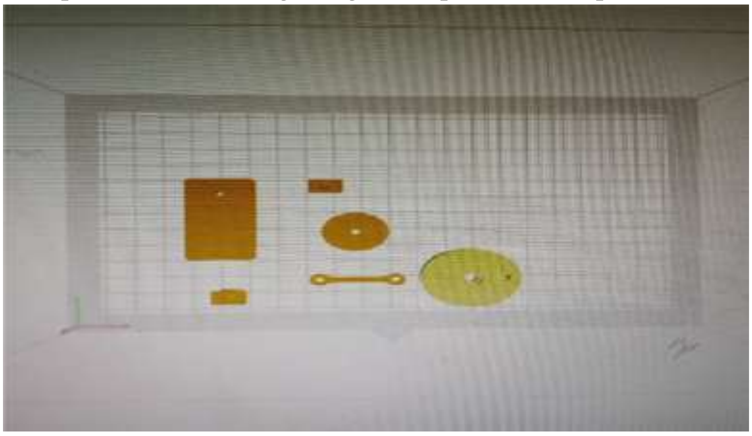
The pinion and rack gear mechanism is a beautiful but efficient mechanical system for the conversion of linear to rotational or rotational to linear motion. It consists of toothed circular gear, or pinion, that overlaps a flat, toothed bar known as the rack. When the pinion rotates, its teeth move into contact with the rack's teeth, which move in a straight line linearly, or, in turn, linear movement of the rack rotates the pinion. The system is appreciated for precision, efficiency, and the ability to transmit force with little backlash. It is used with the highest utility in car steering systems, in which turning of the steering wheel (pinion) is translated to lateral rack motion to steer the car's wheels, offering quick handling. In manufacturing industry, rack and pinion systems drive linear actuators on CNC machines, robot arms, and conveyor belts to position for precise goals. They are also seen in cog railway systems to drive trains to climb steep slopes. They are used in elevators, stage lights, and 3D printers to create controlled vertical or horizontal motion. Despite being powerful, the system should be lubricated periodically to prevent wear and therefore is an optimal solution for motion conversion where a reliable motion conversion is needed.

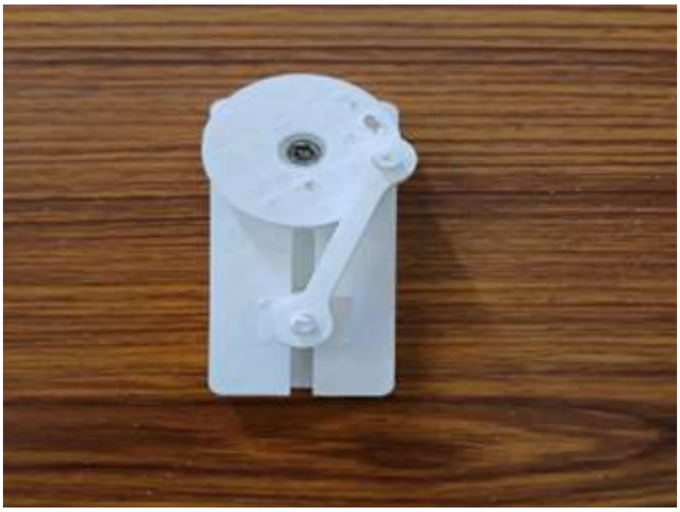




2. SLIDER CRANK MECHANISM

The slider-crank mechanism is a basic mechanical linkage employed to translate rotational motion into linear motion or vice versa, comprising a rotating crank, a connecting rod, and a linearly moving slider. The crank, which is pivoted, rotates, inducing the connecting rod to oscillate and drives the slider along a guided path, usually in a track or cylinder. It is used most essentially in internal combustion engines, where the crank rotation (by the engine's crankshaft) translates the piston (slider) linearly in the cylinder to translate fuel energy into mechanical work. It also drives reciprocating pumps and compressors to enable fluid or gas flow. In machine tools, slider-crank mechanisms power tools such as presses, saws, and sewing machines with accurate linear motion. Slider-crank mechanisms are used in robotics to enable articulated motions, in steam engines to link the wheels' rotation with the movement of pistons, and in exercise machines such as rowing machines to get smooth linear strokes. While effective, the mechanism needs to be well-lubricated in order to reduce wear and is thus an institution in application for dependable motion conversion in car, industrial, and consumer products industries. Furthermore, research published in *Mechanism and Machine Theory* explored the dynamics of a slider-crank mechanism actuated by a spring-damper system. The study utilized multibody simulation environments to analyze the natural motion and optimal working conditions of the mechanism, highlighting the potential of integrating 3D printed components with dynamic systems for advanced applications [8].





3. FOUR BAR MECHANISM

The four-bar mechanism is a mechanical linkage of four pivoted bars in a closed loop, serving as a general-purpose mechanical linkage used to transmit motion and force in a controlled manner. Generally consisting of a fixed link (frame), two turning links (crank and rocker), and a connecting link (coupler), the mechanism produces a wide range of motion patterns, such as oscillation, rotation, or more intricate paths, based on link lengths and configuration. Simple but general, four-bar mechanism finds extensive use in a broad range of applications. In automotive systems, it powers windshield wiper sets, transforming rotation of the motor into sweeping action. It is employed by industrial machines in presses, sewing machines, and conveyor systems to impart precise cyclic motion. In robotics, it is the arrangement of articulated arms and grippers to allow flexible motion. The mechanism is also essential in aircraft landing gear for extension and retraction smoothness. In home appliances, it is used in folding tables and chairs, bicycle suspension systems, and exercise equipment like treadmills for repetitive steady motion. Four-bar linkages are also used in prosthetic limbs to simulate natural joint motion. Being least maintenance-intensive if well designed, the mechanism is essential to applications demanding reliable and adjustable movement in engineering and consumer devices.

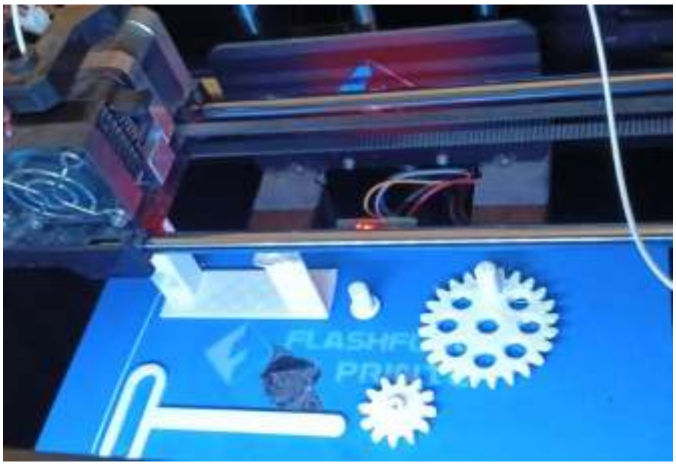
VI. DEVELOPMENT OF LEVEL-3 MECHANISMS

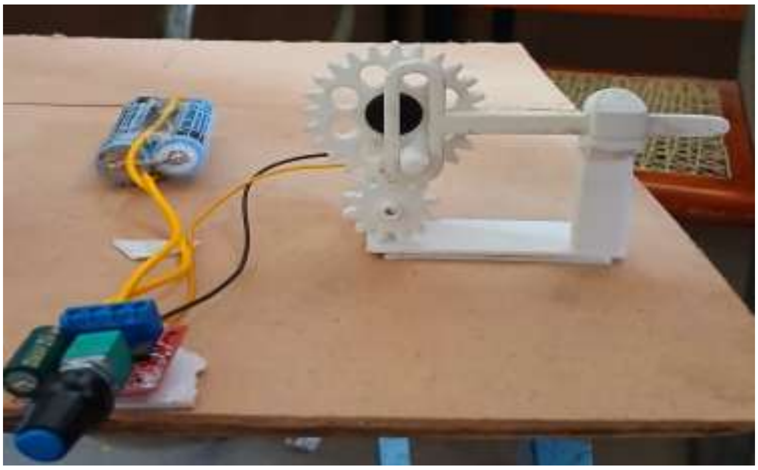
1. SCOTCH AND YOKE MECHANISM

The Scotch yoke mechanism is a machine that converts rotational motion to linear motion or vice versa and is made up of a rotating crank fitted on a sliding yoke with a slot, where the crank has a pin that enters the slot to drive the yoke in a straight line. As the crank rotates, the pin moves along the slot in the yoke, producing smooth, sinusoidal linear motion with constant velocity for parts of the cycle. Priced for its simplicity, compactness, and ability to produce pure linear motion without complex linkages, the Scotch yoke is used in a broad range of applications. It is extensively used in reciprocating pumps and engines, such as small internal combustion engines or air compressors, where it drives pistons with precise linear strokes. In industry, it drives valve actuators for pipelines to provide precise opening and closing. The mechanism is also used in test equipment, such as fatigue testers, to replicate repetitive linear motion. In automation, it

Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

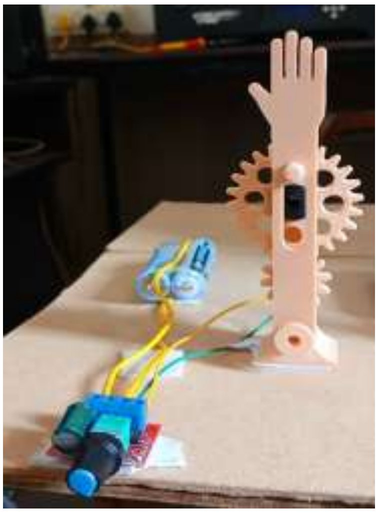
drives linear actuators in packaging or assembly lines. It also finds use in scientific instruments and control systems that need uniform linear displacement. Although robust, the mechanism requires lubrication to reduce wear in the slot, making it ideal for applications that need reliable, uncomplicated motion conversion.





2. WHITWORTH QUICK RETURN MECHANISM

Whitworth quick return mechanism is a mechanical linkage converting rotary to reciprocating motion with unequal working and return stroke time ratio and providing faster return strokes for better efficiency. It is a turning crank on a slotted link, which alternately reciprocates on a pivoted lever arm, moving a reciprocating ram or tool. Through rotation, the lever motion provides a slow, heavy working stroke and rapid return stroke, achieving maximum work cycles. Valued for its compactness and recovery of idle time, the mechanism is utilized extensively in industry. It is used extensively in shaping and slot machines, where precision is attained by the slow cutting stroke and rapid return saves time. It drives mechanical presses and punching machines as well, providing firm, controlled force on the working stroke. It was utilized in early machinery in steam engine-driven tools and early metalworking machines. It is utilized in specialized automation systems requiring asymmetric reciprocating motion, such as in certain packaging or material handling equipment. Although rugged, the mechanism requires regular servicing to prevent wear in the sliding members, and hence appropriate for applications requiring efficient, high-force reciprocation with short cycle time.



VII. INTEGRATION OF IOT SYSTEMS

The convergence of Internet of Things (IoT) technology and 3D-printed kinematic models has been the chief leap forward in the promise of mechanical systems to be continuously monitored, reliably serviced, and even more interactive. This convergence of technology is of particular relevance to Industry 4.0, with automation and smart manufacturing being key.

In the study "Predictive 3D Printing Spare Parts with IoT" by Song and Zhang, the authors explore how IoT-enabled sensors embedded within machinery can communicate operational data to 3D printing systems. The research emphasizes that the true benefit lies in the ability to print predictively, based on system status, rather than on-demand, thereby enhancing efficiency and responsiveness in manufacturing processes [9]. Further, the integration of IoT in 3D printing processes facilitates remote monitoring and control, as demonstrated in the work "Implications of IoT in 3D Printing and Remote Engineering.". Such capabilities are crucial for ensuring print quality, reducing failures, and enabling efficient remote operations [10].

The integration of IoT technology with 3D-printed kinematic devices like Scotch yoke and Whitworth quick return mechanisms provides a promising research area for mechanical engineering. Apart from enhancing the functionality and efficiency of such mechanisms, fusion also provides potential for innovation in smart manufacturing, automation, and educational aids.

VIII. CONCLUSION

The combination of 3D printing technology and IoT-enabled microcontrollers in the development of kinematic models is a revolution in the mechanical design and automation process. With additive manufacturing, complex mechanical systems such as linkages and gears can be rapidly prototyped, customized, and optimized for learning and real-world use. The addition of IoT allows real-time motion control, monitoring, and visualization, making the models interactive as well as multi-purpose for real-world use. This process enhances learning by integrating theoretical concepts with experimental hands-on experiments, which encourage innovation among educators and students. Finally, the combination of 3D printing and IoT in the development of dynamic, scalable, and intelligent kinematic systems makes it a revolutionary tool in engineering education and mechanical system development.

IX. REFRENCES

1. Xu, J., Xueqing, F., Jun, C., & Shuyou, Z. (2020). Precision forward design for 3D printing using kinematic sensitivity via Jacobian matrix considering uncertainty. *The International Journal of Advanced Manufacturing Technology, 110*(9–10), 3257–3271. https://doi.org/10.1007/s00170-020-05940-4:contentReference[oaicite:0]{index=0}

2. Dumlu, A., Mahboubkhah, M., Ayten, K. K., & Kalınay, G. (2022). Mathematical analysis and design of a novel 5-DOF 3D printer robotic system. *Elektronika ir Elektrotechnika*, 28(4), 4–12. https://doi.org/10.5755/j02.eie.31383

3. Avdeev, A. R., Shvets, A. A., & Torubarov, I. S. (2019). Investigation of kinematics of 3D printer print head moving systems. In A. A. Azarov (Ed.), *Proceedings of the 5th International Conference on Industrial Engineering (ICIE 2019)* (pp. 461–471). Springer. https://doi.org/10.1007/978-3-030-22041-9_50:contentReference[oaicite:1]{index=1}

4. Zheng, C., Kim, J., Leithinger, D., Gross, M. D., & Do, E. Y.-L. (2022). Kinergy: Creating 3D printable motion using embedded kinetic energy. *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*, 1–13. https://doi.org/10.1145/3526113.3545636

5. Zhang, Y., Li, X., Wang, M., & Chen, Y. (2023). Exploring the Integration of IoT in 3D-Printed Kinematic Mechanisms. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery. https://doi.org/10.1145/3544548.3581440:contentReference[oaicite:0]{index=0}

6. Lipson, H., & Kurman, M. (2006). 3D Printing the History of Mechanisms. *Cornell University Library*. Retrieved from https://ecommons.cornell.edu/items/36141118-960a-45c4-9bab-7e5a7f9247e1

7. Ramesh, B. T. (2022). Design and analysis of knuckle joint by using Solid Edge and ANSYS. *International Journal of Engineering Research & Technology (IJERT)*, *11*(5), 1–5. Retrieved from https://www.ijert.org/design-and-analysis-of-knuckle-joint-by-using-solid-edge-and-ansys:contentReference[oaicite:1]{index=1}

8. González, R., & Cuadrado, J. (2021). Analysis of the dynamics of a slider-crank mechanism with elastic joints and control strategies. *Mechanism and Machine Theory, 157*, 104204. https://doi.org/10.1016/j.mechmachtheory.2021.104204

9. Song, J.-S. J., & Zhang, Y. (2023). Predictive 3D printing spare parts with IoT. *SSRN*. https://doi.org/10.2139/ssrn.3895854

10. Aradhya, A. M. (2020). Implications of IoT in 3D printing and remote engineering: Using open-source hardware and software. In M. E. Auer (Ed.), *Cross reality and data science in engineering* (pp. 667–673). Springer. https://doi.org/10.1007/978-3-030-52575-0_55