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Development of a Drive Unit for a Cost-effective Follow-focus Control System

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ABSTRACT

Objectives - This study compares the most affordable stepper motors currently available for suitability as the main component of the drive unit for the development of a cost-effective Follow-focus Control System for deployment in Higher Education in photography.

Methodology - Applying a quantitative approach through a prototype design methodology the required criteria of speed, torque and accuracy were defined and the candidate stepper motors' performance compared to a theoretical ideal to define their suitability.

Findings - A testing process that artificially simulated general, real-world, use-cases revealed that both candidates, the 28BYJ-48 stepper motor and the 17HS2408 Nema 17 stepper motor, met the required torque and speed metric of facilitating high-speed focus shifts in one second without introducing unwanted camera movement, skipping steps or introducing vibration while maintaining focus accuracy within the defined accuracy metric as determined by focus charts. Both candidates also completed low-speed focus shifts over a set period of 10 seconds to assess smoothness of the resultant focus shifts without introducing unwanted camera movement or vibration while maintaining focus accuracy within the defined accuracy metric. These results illustrated both of the candidate stepper motors met the required testing metric needed to serve as the main component of a Follow-focus control system drive unit. These finding now offer a clear and concrete departure point in discrete component for the development of a drive unit for a follow focus control system.

Application - It is recommended that the 28BYJ-48 stepper motor be deployed for the development of a cost-effective Follow-focus control system drive unit due to its lower price combined with torque and accuracy metrics that fall within the defined range of acceptable performance for industry application.

1. Introduction

Being able to participate actively and physically in one's own learning experiences could mean the difference between success and failure in a technology-dependent subject field. The theory of learning-by-doing is well researched and even being able to actively use one's hands during a demonstration lesson has shown better visual attention and deeper processing of information [1]. This means, that for a student to master a specific technology, they need hands-on exposure to industry-relevant equipment to prepare them for the workplace.

Financial resources have become a major constraining factor for both institutions in Higher Education (HE) as well as students and graduates in developing countries, like South Africa (SA), owing to prevalent socio-economic issues such as the income gap [2]. This has a negative impact on graduate industry preparedness and entrepreneurship as the expense of industry-standard equipment such as spectrum analyzers, scanning electron microscopes and photographic equipment restrict academic institutions from purchasing the number of units required to facilitate adequate equipment training and access for the volume of students enrolled in a course. The high cost of equipment also further limits graduates' ability to strike out as entrepreneurs once they have completed their qualification [3]. Not being able to provide an adequate number of photographic tools that are capable of creating professional-grade work prohibits students in photographic disciplines from receiving the needed hands-on work over a period of time, thereby limiting their effective participation in their local communities.

Development of cost-effective, open-source, yet still industry-standard photographic tools, such as a Follow Focus Control System (FFCS), built from off the shelf parts has the potential to allow students easier access to industry-relevant equipment where they can acquire over time more "hand-on" practice. Regular engagement with such a system could also empower students with new entrepreneurial skills and technological skills for innovation. This paper aims to test two reasonably priced off the shelf stepper motor configurations for suitability as the main component of an FFCS drive unit that compares with its current industry-standard counterpart. Determining the most financially viable stepper motor that meets required performance levels to serve as an off the shelf part in developing an FFCS drive unit could assist in developing the most cost-effective FFCS for deployment in HE and as a viable option for graduates starting to assemble an equipment base for entrepreneurial ventures in the photographic industry.

This paper will firstly explore current literature on photographic motion capture and the evolution of the technology used therein followed by the context and methods used. Finally, the testing of the prototype and its results will be discussed.

2. Literature review

Along with the birth of photographic motion capture and development of cinema came the need to solve new problems unique to this aspect of photography which is the ability to accurately and inaudibly control the focus and position of the camera. Moving the camera during filming is a critical part of effective storytelling in cinema and actors are rarely static during any part of a scene. The process of moving the camera was largely a manual process through the use of track systems known as a Dolly or counterweighted cranes, also referred to as a Jib, or a mixture of these devices (see fig. 1) [4]. Motion on the part of the camera, or the part of a subject, will likely result in a change in distance that will necessitate the need for adjusting the focus to accommodate for this. The first systems developed to do this were also manual rack and pinion based systems [5] developed as a byproduct of employing camera-specific housings to dampen the sound of noisy camera mechanisms [6]. Only once these systems started being employed as modular systems with universal mount and drive gears did the industry term Follow-Focus emerge for such a tool [7]. These systems further evolved from basic manual drive systems as shown in Figure 2 to much more complex electronic systems like the Tilta Nucleus shown in Figure 3.

Figure 1: Three Camera operators push a dolly while a fouth controls pan and tilt on the set of StarWars: A New Hope, 1976 [8]

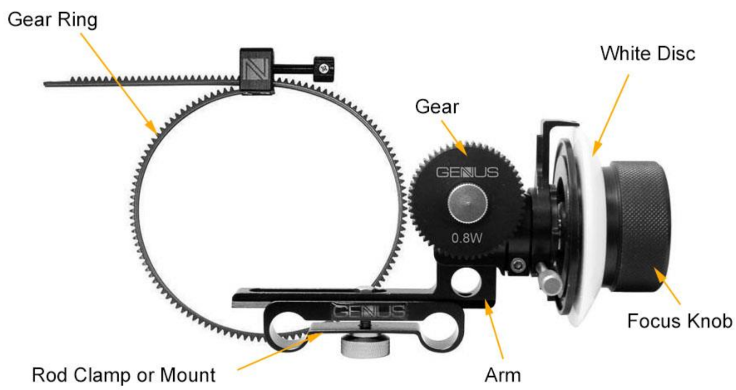

Figure 2 Manual follow-focus unit with a lens gear ring [9]

Figure 3: Modern electronic follow-focus control system [10]

Photography often requires that multiple mechanical devices be utilized in precisely synchronized unison that results in an aesthetically pleasing camera movement and corresponding focus shift which will be executed by as many as 3 individual crew members [4]. The manual process of creating these movements are then highly likely to be plagued by mistakes caused by operator error. Advances in microcontroller technology allowed Hollywood filmmakers, such as Industrial Light and Magic, to develop new and vastly superior niché tools for accomplishing the same motion and focus control, but with the accuracy and repeatability of a Computer Numerical Control system [11]. The accessibility of high-quality recordings outside of high-end movie productions and the evolution of affordable ultra-high-resolution Video Digital Single Lens Reflex Cameras (VDSLR) have created a need for equally accessible motion and focus control tools for small businesses and entrepreneurial photographers. Open-source projects driven by enthusiast communities have attempted to address some of these needs, but the major challenge with some of these projects is that they are only accessible by individuals who possess functional knowledge of electronics and resources that are regularly available in first-world countries [12]. However, System on a Chip (SoC) devices, like Arduino, has allowed easy access to microcontrollers and the skills to program them, opening the door to prototype and develop all manner of precision-controlled tools such as the ones required by photographers [13].

Though there has been a small amount of academic research into the utilization SoC's in the development of motion or focus control systems in the application of photography, the research is rudimentary [14]. Research has not focused on achieving cost-effectiveness or is applied in scientific applications that merely seek to meet specific documentation requirements and do not emphasize creative or aesthetic implementation [15] [16]. A second issue with a host of currently available academic research in this field is that much of it is merely aimed at providing "proof of concept". However, research by Hoesl, Mörwald Burgdorf, Dreßler and Butz [11] was found to detail a complete project to the point where it was fully functional. The aforementioned research strove to develop an affordable and open source single-axis motion control system and an automated software control platform with a Graphical User Interface with high mobility for use in the field. Although this single-axis motion control system aligned with the goal of affordability, its main focus was skewed more toward the process of developing the control system and gauging the effect of levels of automation on the final resultant media. This left the development of a complete and integrated system largely unexplored.

3. Context

Universities of Technology (UoT) in SA trace their origins to what were termed "Technical Colleges" which were academic institutions with a primary focus on vocational training to serve industry needs [17]. One of the Diploma's, offered at many of these universities in SA, focus on Design and Studio Art [18]. The Central University of Technology (CUT) lists the following Expected Learning Outcome (ELO) for the module Digital Imaging (SDP6001 that forms part of the curriculum for this Diploma) in the study guide:

"*This module aims to transpose the core skill of utilizing a digital capture device and accompanying tools for the purpose of capturing both still images and video with a thorough underpinning of understanding light and technical proficiency in the application of lighting."*

The above-stated ELO summarises the content of the three-year process that aims to facilitate proficiency in the application of VDSLR cameras in the creation of images and video for aesthetic and creative purposes. As part of this process, students implement 3-axis gimbals and motion-controlled dollies in the creation of video, timelapse and stop-motion animation. All of these techniques implement camera movements and thus require the use of a follow focus system. This exposure to industry-standard techniques and equipment is harnessed in an attempt to allow students as much tactile, engaging practical experience with digital image capture as possible in an attempt to maximize proficiency before their exit into the industry. CUT caters to the central region of SA and has approximately 78 students enrolled for the second year of the Diploma that all need to access this type of equipment over a limited period of time. Purchasing industry-standard photographic equipment for all these students is not a viable option, and thus requires the development of cost-effective FFCS that includes specific drive (stepper) motors.

4. Methods

The stepper motors selected for comparison and assessment in this paper are the ubiquitous 28BYJ-48 monopolar motor and the 17HS2408 bipolar motor packaged in the popular Nema 17 form factor which was chosen primarily based on the fact that they were the lowest priced units regularly available from electronics retailers in SA. Further secondary considerations were given to the amount of current drawn to improve suitability for battery-powered implementation and torque rating of the stepper motor. When comparing these criteria in Table 1 below the 28BYJ-48 scored highly in all criteria and was the most cost-effective unit that could be sourced. The 28BYJ-48 stepper motor was purchased from a local SA supplier for the amount of ZAR R 35.95 (USD $2.18) [19] and is available from many online stores both nationally and internationally at a similar price-point. The 17HS2408 is, unfortunately, more than three times the price as purchased from an international online retailer for the price of ZAR R 129.30 (USD $7.80). Even though it is much more expensive than the 28BYJ-48, it is the nearest affordable price competitor that could be obtained.

Table 1: Stepper motor specifications

Stepper motor	**28BYJ-48**[20]	**17HS2408**[21]
Current per phase	200 mA	600 mA
Torque	2.9 N.cm	12 N.cm
Angle per step	5.625°	1.8°
Gear ratio	64:1	None
Angle per step of driveshaft	0.0879°	1.8000°
Retail price in South Africa	R 35.95	R 129.30

As this paper is concerned purely with defining the possible suitability of two stepper motors for implementation within a drive unit of an FFCS, with measurable performance criteria that can be judged empirically or objectively, its focus will be purely quantitative [22]. The research is further driven by the development of a prototype as evidence that specific design criteria can be met and is ideally suited to the implementation of a Prototype Design Methodology (PDM) [23]. The choice of PDM is further reinforced by the proven efficacy and high likelihood of this methodology in meeting specific requirements and design goals [24].

The testing criteria for PDM in this instance were devised by assessing the most commonly used implementations of commercially available FFCS' and their functions within these implementations for creating media. The functions, as listed below, were defined as core requirements to be performed in a controlled test environment utilizing the candidate stepper motors as the main component of the drive unit for the FFCS. The subsequent media was then evaluated to determine whether the functions were performed to industry-standard expectations.

- Ability to shift focus from one plane to another very slowly (tracking a subject) while the camera motion control is employed without introducing vibration or camera motion which would render the focus shift noticeable.
- Shift focus at high speed to track a rapidly moving object without introducing vibration or camera motion which would render the focus shift noticeable.
- Shift focus from one preset position to another position for multiple numbers of times with high enough precision that the resultant footage can be used to create composite footage in post-production for special effects purposes.

5. Prototype testing

When analyzing the currently available commercial FFCS' that perform at industry acceptable levels and their most used implementations form the previous section; the key performance areas that were apparent were smoothness of focus shift at both high and low speed, repeatability, and precision. Thus, the following prototype tests were devised to assess the ability of the cost-effective stepper motors of fulfilling the aforementioned criteria:

- Shift focus from three predefined focus points at low speed, taking 10 seconds to shift focus from one point to the next. Cycle between predefined focus points on a preset routine following the same routine both forwards and in reverse 10 times to assess the accuracy and repeatability.
- Shift focus from three predefined focus points at high speed, taking no more than 1 second to shift focus from one point to the next. Cycle between predefined focus points on a preset routine following the same routine both forwards and in reverse 10 times to assess the accuracy and repeatability.

This combination of high and low speed, predefined focus points, and repetition assured that all industry-relevant criteria are assessed with the particulars of the testing discussed in the following section. The testbed for the prototype testing is a Nikon D850 camera that is capable of recording video with a resolution of 3840 x 2160 pixels (4K) at 24 frames a second encoded in H.264 MP4 format, with the higher resolution of the recording aiding in the assessment of precision and smoothness of focus shift. A Nikon AF-S 50mm *f*1.8 lens was selected and implemented at an aperture of *f*2 to facilitate a narrower plane of focus and thus allow a more critical assessment of motor performance while maintaining a wide enough angle of view at 50 mm focal length to not have the foreground objects obscure the objects behind it. The Camera and lens were mounted on a Manfrotto MVH502A tripod head on a set of Gitzo GT3531LSV tripod legs. This camera support combination was chosen due to its stable load rating being more than triple of that required and thus the decreased likelihood of the support system introducing external motion or vibration that could be misconstrued as vibration or motion introduced by

the FFCS drive unit. The recording was initialized before each test cycle with the researcher audibly announcing the testing parameters before commencements for later reference.
To assure an accurate and fair comparison between the two motors, and to ease implementation, the 28BYJ-48 was converted from monopolar to bipolar by following the simple, popular and well-documented process of severing the trace connection on the motor circuit board [25]. The motivation for this conversion was to implements the same bipolar stepper driver for both motors, a Pololu A4988 set to 1/8 micro-stepping, which would assure an accurate comparison. To facilitate mounting of the motors the camera was attached to an industry-standard Light Weight Support rail system which features 15 mm rails for attaching FFCS’. A rudimentary mounting frame was designed with the help of Computer-Aided Design software and 3D printed via Fused Deposition Modelling (FDM). To facilitate compatibility with the industry-standard 0.8 modulus FFCS gear, a gear was designed and printed to attach directly to the 28BYJ-48 (Figure 4) owing to its internal 64:1 gear ratio and a geared pulley with a reduction of 2.5:1 via a GT2 drive belt was printed for the 17HS2408 motor (Figure 5). These 3D printed parts are indicated with red arrows in the figures.

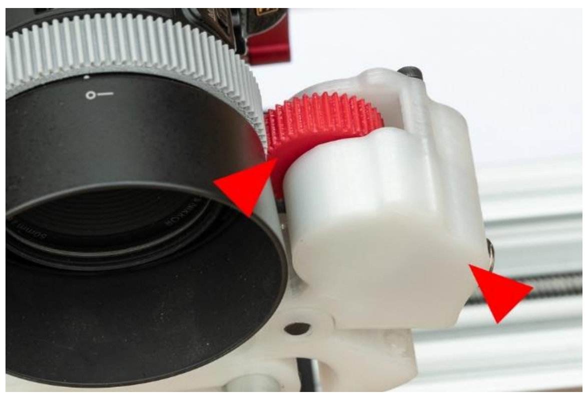

Figure 4: 3D printed parts for mounting 28BYJ-48

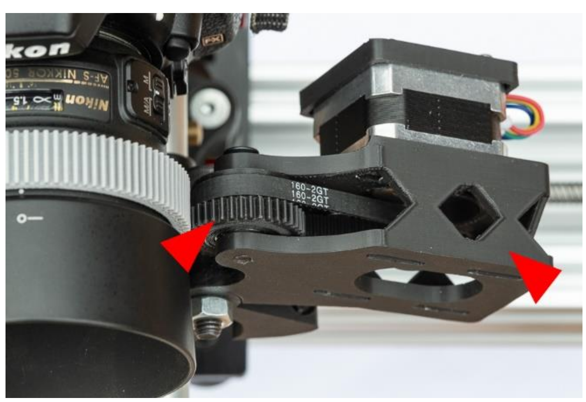

Figure 5: 3D printed parts for mounting 17HS2408
For testing, a Focus Testing Chart (FTC) with a clear centre marking and graduating scale marked in millimetres and centimetres (see Figure 6), as designed by Friedl [26] was placed at intervals of 500 mm, 1000 mm, and 1500

mm from the camera. Focus testing charts were placed as near as possible to the centre of the image frame without the charts obscuring each other. This was done to ease the assessment of resultant media by maximizing the sharpness of the image and avoiding any potential softening near the edges of the captured image due to limitations of the lens design [27]. Through the use of a Depth of Field calculator, it was determined that this camera and lens combination resulted in a plane of acceptable focus that is 100 mm in depths for the shortest used focusing distance, with anything 50 mm closer to or further away from the focal point being deemed as out of focus.

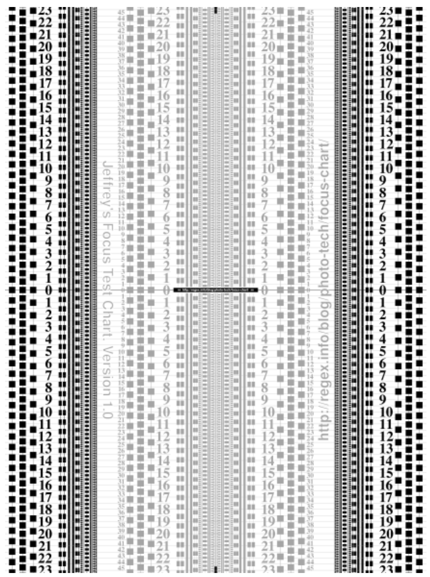

Figure 6: Focus testing chart [26]

An Arduino Mega 2560 was programmed to drive a stepper motor via the Pololu A4988 with the motor jogged to the three respective waypoints that resulted in the centre of the focal plane coinciding with the marked middle point of the FTC and the waypoint position stored. The first waypoint being the nearest focus chart's middle mark (see Figure 7, lens focus scale highlighted in red), the second being the furthest focus chart's middle mark and finally, the third being with the FTC set at 1000 mm (see Figure 8, lens focus scale highlighted in red). The correct focus position was visually confirmed at 100% magnification via the rear display of the camera before recording the waypoint. The high- and low-speed tests were then commenced with non-linear Brézier curve applied to acceleration and deceleration comprising 5% of total travel respectively for each waypoint to minimize motion introduced by acceleration and deceleration torque.

Figure 7: Camera focused on the nearest FTC (500 mm)

Figure 7: Camera focused on the middle FTC (1000 mm)

Successful completion and thus suitability for use in an FFCS drive unit would be constituted by the following:

- Ability to complete the high-speed waypoint cycle 10 times with the middle mark of each FTC remaining within the zone of acceptable focus as determined by the Depth of Field calculator and utilization of the focus chart as evidence.
- Ability to complete the low-speed waypoint cycle 10 times with the middle mark of each FTC remaining within the zone of acceptable focus as determined by the Depth of Field calculator and utilization of the FTC as evidence.
- Complete both tests without introducing any form of vibration or motion to the camera that is visually apparent in the resultant media playback.

6. Results and discussions

The following tables illustrate the results recorded during the completion of the high-speed and low-speed tests of the 28BYJ-48 (Table 2) motor and the 17HS2408 Nema 17 motor (Table 3).

Table 2: 28BYJ-48 Results

Number of cycles	Travel time between points	Speed achieved	Noticeable motion introduced by focus shift	Industry-level performance
20	10 seconds	Yes	None	Pass
20	5 seconds	Yes	None	Pass
20	2 seconds	Yes	None	Pass
20	1 second	Yes	None	Pass

2	800 milliseconds	Yes	Yes	Outside testing metric
0	400 milliseconds	No	Motor stutter prevented the test	Outside testing metric

Table 3:17HS2408 Results

Number of cycles	Travel time between points	Speed achieved	Noticeable motion introduced by focus shift	Industry-level performance
20	10 seconds	Yes	None	Pass
20	5 seconds	Yes	None	Pass
20	2 seconds	Yes	None	Pass
20	1 second	Yes	None	Pass
2	800 milliseconds	Yes	Yes	Outside testing metric
2	400 milliseconds	Yes	Yes	Outside testing metric

The 28BYJ-48 stepper motor completed both the high-speed and low-speed test while successfully keeping the middle point of the FTC centre mark within the plane of acceptable focus. Although the motor did succeed within the defined metric, it did come noticeably close to exhibiting an unacceptable deviation of the focal plane that would have deemed it unacceptable for this implementation. A similar deviation of the focal plane was noted during the execution of the slow-speed test. Visual observation and extended testing revealed that this deviation of the focal plane occurred as a cumulative effect of backlash present in the reduction gearing mechanism of the 28BYJ-48 which was compounded by backlash present in the mechanical focus mechanism of the lens itself.

The 17HS2408 Nema 17 stepper motor also successfully completed both the high-speed test as well as the low-speed test while exhibiting an appreciably smaller deviation of the focus plane. This, as noted above, was caused by compounding backlash introduced by the GT2 timing belt and the focus mechanism of the lens, but the drive reduction employed by the Nema 17 test setup resulted in less backlash and thus less deviation.

Further testing beyond the metric set by the testing criteria revealed that both stepper motors were capable of focus shifts faster than the required 1 second, but focus shifts of this velocity introduced an unwanted motion in the resultant footage once the drive motor attempted to facilitate this shift at well below sub-one second periods. The motion was only introduced in the shift from 500 mm to 1500 mm when speeds were achievable. Thus, considerations to supporting the lens, camera or both should be made if very high-velocity shifts are to be considered.

7. Conclusion

This paper aimed to test two reasonably priced off the shelf stepper motor configurations for suitability as the main component of an FFCS drive unit that compares with its current industry-standard counterparts.

The candidate stepper motors, chosen for their low cost to performance ratio, were the 28BYJ-48 and 17HS2408 Nema 17 stepper motors. When considering the results, both motors were able to shift focus between defined focal points in one second and tens seconds without the introduction of camera motion or vibration. This indicates that both would be suited for implementation in an FFCS as their performance falls well within the required metric of industry-standard use-cases.

The proven acceptable performance and very low price of the 28BYJ-48 stepper motor rendered it uniquely suited for inclusion in an FFCS drive unit to allow greater access for students to industry-standard equipment and assist in learning critically relevant skill to allow greater industry preparedness and a more engaging learning environment. If higher precision is required for application with lenses capable of shallower Depth of Field or larger heavier lenses are implemented, then the higher-priced 17HS2408 Nema 17 unit would be recommended due to its higher torque specification and a higher degree of accuracy as discerned in the testing process.

No consideration has been given to the potential lifespan of the gear reduction mechanism of the 28BYJ-48 and long term use might show a decrease in accuracy due to wear. It can also be suggested that additional support for the lens or camera body might allow for more rapid focus shifts than tested and is highly recommended for any FFCS drive implementations such as the one tested here.

Implementation of cost-effective components with proven performance such as the 28BYJ-48 stepper motor has the real potential to make a measurable difference in the academic engagement of tertiary education students by allowing access to previously unattainable tools. This could allow for a more engaging and complete learning experience and greater potential for entrepreneurial endeavours.

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