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Revolutionizing Palm Dates Harvesting with Multirotor Flying Vehicles

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Abstract: This study addresses the challenges of traditional date palm harvesting, which is often labor-intensive and hazardous, by introducing an innovative solution utilizing multirotor flying vehicles (MRFVs). Unlike conventional methods such as hydraulic lifts and ground-based robotic manipulators, the proposed system integrates a quadrotor equipped with a winch and a suspended robotic arm with a precision saw. Controlled remotely via a mobile application, the quadrotor navigates to targeted branches on the date palm tree, where the robotic arm, guided by live video feedback from integrated cameras, accurately severs the branches. Extensive testing in a controlled environment demonstrates the system's potential to significantly improve harvesting efficiency, safety, and cost-effectiveness. This approach offers a promising alternative to traditional harvesting methods, providing a scalable solution for date palm cultivation, particularly in regions with large-scale plantations. This work marks a significant advancement in the field of agricultural automation, offering a safer, more efficient method for harvesting date palms and contributing to the growing body of knowledge in automated farming technologies.

Keywords: drones; Pixhawk; harvesting; date palm; robotic arm; 3D printers

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1. Introduction

Date palm trees (Phoenix dactylifera) are tall trees that grow to heights of up to 24 m [1]. They are characterized by cylindrical stipes (trunks) over which a crown of leaves develops. Among the leaves are the branches that carry the sought-after date fruits. Date palm is cultivated in over 30 different countries with production totaling approximately 9.7 million tons [2,3].

The Kingdom of Saudi Arabia is among the top producers of dates with an annual yield of approximately 1.5 million metric tons [4]. The kingdom is estimated to have over 31 million date palm trees [4] distributed across various regions of the country. There are thousands of date farms in the Kingdom ranging from small family-owned farms to large commercial operations. These farms are spread throughout the country, with significant concentrations in regions like Al-Qassim, Al-Ahsa, and Al-Madinah [5].

Despite the huge production, harvesting of date palm has seen little advancements with regard to mechanization. For instance, the majority of the harvested date palms worldwide are done manually. This usually involves a harvester, with a rope wrapped around his back and the date palm trunk, climbing the trees and manually harvesting the fruit [6–10] as shown in Figure 1. The actual harvesting may involve plucking the fruits one by one, shaking the bunch to cause the fruits to fall, or cutting the entire bunch when they are deemed to be ready for harvesting [11]. Each of these techniques requires a skilled harvester, is physically demanding, and is quite dangerous. In some instances, harvesters utilize ladders, which enable the harvesting of date fruits for shorter palms. Ladders are also used to reduce the climbing to the upper section of the high palms and they are generally utilized without safety measures and may be more dangerous than the climbing method. Tragically, numerous accidents have occurred, resulting in fatal falls from these towering trees [12].

Figure 1. Harvesting date palms by climbing trees.

Various mechanical systems employing hydraulic lifts and additional apparatus such as forklift towers and cranes have been employed to access dates on lofty trees [13,14], Figure 2. There have been endeavors to adapt industrial machinery for date palm harvesting, particularly in the Kingdom of Saudi Arabia [9,15–17]. However, these machines come with substantial costs and require a substantial workforce to operate. Furthermore, their ability to reach exceedingly tall trees is limited, imposing constraints on their utility. Moreover, workers may be unavailable in certain situations, such as during the COVID-19 crisis, which greatly reduced the date harvesting process and caused significant losses.

An alternative approach involved the utilization of portable date bunch harvesting machines operated from the ground, as documented in [9]. This method entails the use of an electric saw to sever date bunches at a maximum height of approximately 8 m, followed by the retrieval of the branches.

Some researchers have advocated for the deployment of robotic arm manipulators affixed to ground vehicles for date palm harvesting [7,16,18]. However, these ground vehicles are often cumbersome and may encounter difficulties traversing dense palm tree fields [19]. Moreover, the manipulator arms have finite reach capabilities, rendering them inadequate for harvesting exceptionally tall trees, Figure 3.

After an extensive search in the literature, the authors were only able to identify a few studies addressing the modernization of date harvesting as is the case with other fruits such as apples [20–27]. This is despite the enormous production of dates annually and the costs and risks involved in the widely used traditional procedure for date harvesting. As for the previously mentioned date harvesting approaches and proposed tools, they have faced limited adoption, particularly on smaller farms, for several reasons:

1. Costly investment: The expense associated with these machines constitutes a significant barrier to their widespread use.
2. Lack of familiarity: Many farmers are unfamiliar with these machines, contributing to a reluctance to integrate them into their practices.
3. Challenging mobility: Maneuvering these machines amid palm trees poses practical difficulties, further impeding their application.

4. Specialized training: Operating these machines demands specialized training, which may not be readily available to all farmers.
5. Limited availability: There is often a scarcity of these machines during the critical harvesting period, limiting their accessibility to farmers.

Figure 2. Hydraulic lift for palm tree harvesting.

Figure 3. Robotic arm for date harvesting [16].

To address the challenges of traditional date harvesting, it is proposed to leverage multirotor flying vehicles (MRFVs), such as quadrotors, to improve efficiency and reduce labor costs. MRFVs offer several advantages, including cost-effectiveness, versatility, and the ability to access tall trees and hard-to-reach areas with ease [28]. By equipping these aerial vehicles with specialized tools like laser modules or mechanized saws, they can be used to precisely cut date branches without damaging the tree. After severing the branches, another set of quadrotors—or even a coordinated fleet of multiple MRFVs—can be deployed to transport the harvested dates clusters to a central collection point. This eliminates the need for ground-based machinery and reduces human labor involvement in the physically demanding task of climbing trees and manually cutting branches. By automating these stages of the harvesting process, the use of MRFVs enhances safety and expedites harvesting, making it more scalable and practical, especially in large date farms.

This work presents an innovative solution for date harvesting by integrating advanced robotic arm technology with a quadrotor system, specifically designed to address the unique challenges of harvesting tall date palms. Unlike traditional methods that rely on manual labor and present safety risks, our system enhances operational efficiency while significantly reducing the risk of accidents associated with working at great heights. The use of a remote-controlled, autonomous robotic arm marks a significant advancement, offering a versatile and cost-effective solution for the agricultural sector. Overall, this research contributes to the growing body of knowledge on automated agricultural practices, particularly in regions where date palm cultivation is widespread.

The rest of the paper is organized as follows: Section 2 presents the proposed system with detailed explanations of each component. Section 3 summarizes the testing procedures, followed by the flight response analysis in Section 4. Finally, the conclusions and recommendations are provided in Section 5.

2. Proposed Harvesting System

The initial concept revolved around approaching the palm branch laterally and utilizing a laser module affixed to a multirotor flying vehicle (MRFV) for cutting. However, thorough investigations revealed the impracticality of this solution due to the laser module's insufficient power. As a result, the MRFV would need to get dangerously close to the branch to perform the cut, which posed significant obstacles.

Subsequently, an alternative idea was proposed, involving a robot equipped with multiple articulating links to wield either a laser gun or a saw. This robot could be situated beneath the quadrotor's frame. However, upon assessing the dimensions of the robotic arm, it became evident that it would require a robust servo and lengthy links, rendering this proposal unfeasible. Additionally, the flexibility of an extended robotic arm presented further challenges.

Ultimately, a decision was made to approach the branch from above and suspend the cutting tool (the saw) using a lengthy wire, hanging from an MRFV. The recommended system comprises a quadrotor flying vehicle with a winch mounted beneath it to support a suspended manipulator arm equipped with a saw mechanism, Figure 4. The quadrotor is equipped with an autopilot and a Raspberry Pi (RPI) companion computer linked to a depth camera. A mobile application has been developed for remote control of both the quadrotor's movements and the operation of the saw-equipped arm. Additionally, this application facilitates the viewing of live video feeds from cameras fixed on both the quadrotor's body and the robotic arm. The quadrotor transports the robotic arm to the date palm branch, and the saw mechanism is employed to execute the cut, with the branch securely held by an end effector attached to the arm.

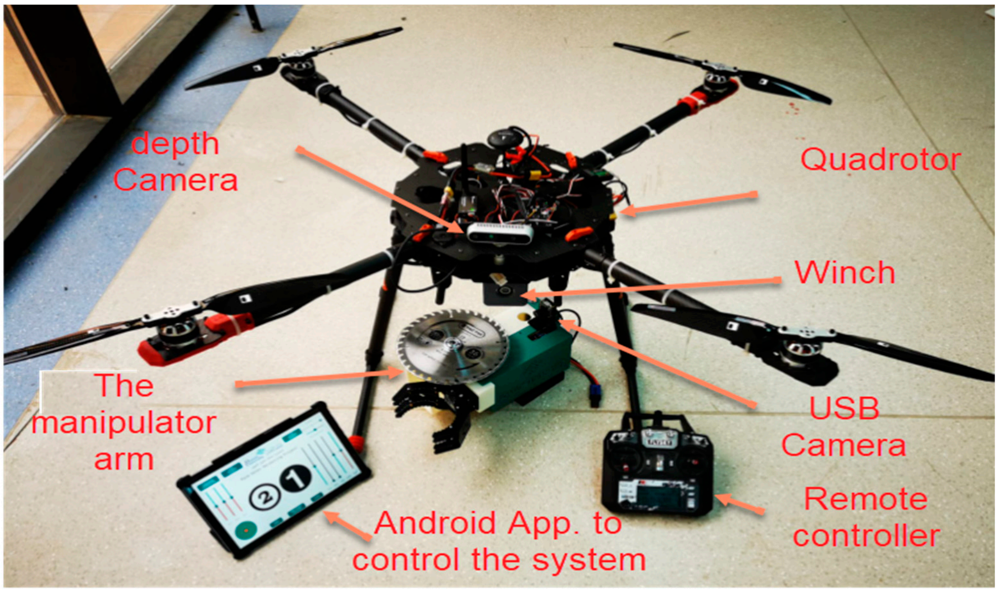


Figure 4. Developed system.

2.1. Robotic Arm System

The robotic arm takes on the crucial task of grasping and severing the palm branch, comprising three essential components: a saw, a linear actuator, and an end effector, as shown in Figure 5. These components are seamlessly integrated within a purpose-built housing, meticulously designed to ensure the system's flawless and efficient operation.

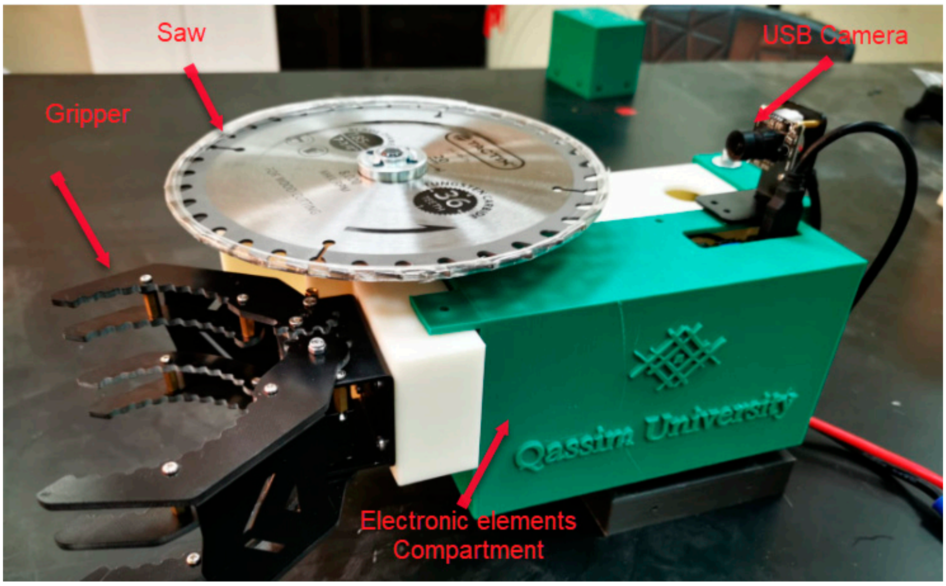


Figure 5. Robotic arm.

The arm housing, along with other related housings, is manufactured utilizing the 3D printing technique, employing ABS filament as the material of choice. The design and specifications of the arm housing, as well as its associated components, were initially conceived using the CAD software Solidworks (2015).

Within the system, the gripper plays a pivotal role in capturing and securely holding the target branch. Subsequently, the 10 cm stroke linear actuator takes charge of propelling the saw, which is affixed to a DC motor, facilitating the cutting process.

The housing itself is thoughtfully engineered to accommodate not only the various elements of the robotic arm but also essential components like a companion computer (Raspberry Pi), a USB camera, a battery, and the array of electronic components indispensable for the seamless operation of the robotic arm.

2.2. Winch

The winch, situated at the base of the quadrotor, assumes the pivotal role of raising and lowering the robotic arm. Comprising essential components, the winch assembly includes a DC motor, a motor bracket, a flexible coupling, a pulley, a shaft, and two bearings, as shown in Figure 6. To house and support these elements, a specially designed housing structure is employed.

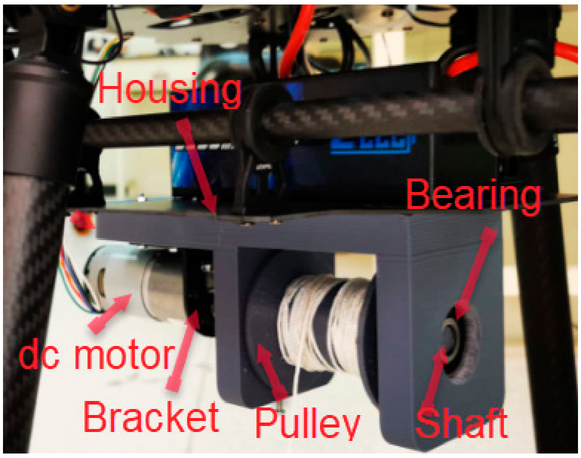


Figure 6. The designed winch.

To ensure the stability of the robotic arm and prevent unwanted twisting, a total of four wires are employed within this winch system. Notably, the housing, pulley, and shaft are meticulously crafted using the 3D printing technique, utilizing ABS filament. The intricate 3D models of these components, including the housing, pulley, and shaft, were meticulously crafted using Solidworks software.

2.3. Quadrotor Flying Vehicle

The quadrotor is a complex assembly, incorporating various vital components such as a frame, brushless DC motor, electronic speed controllers (ESC), GPS unit, telemetry system, LiPo batteries, and more. In addition to these fundamental elements, the quadrotor is equipped with a Raspberry Pi companion computer, a depth camera, and the requisite electrical components to power both the quadrotor and the Raspberry Pi, as shown in Figure 7 and Table 1.

Table 1. Quadrotor components.

No.	Item Description (https://www.kdedirect.com/)
1	Tarot X4 Heavy Lift Professional UAV Quadcopter Frame that can carry up to 8 kg payload
2	Four brushless DC motors from KDE direct, KDE3510XF-715.
3	Four 55 Ampere electronic speed controllers (ESC) from KDE direct company, KDEXF-UAS55
4	Four foldable propellers with their adapters from KDE with, KDE-CF155-DP
5	Pixhawk 1 flight controller from Holybro that run PX4 firmware
6	M8N GPS from Holybro
7	RC receiver from Flysky with its transmitter

Table 1. *Cont.*

No.	Item Description (https://www.kdedirect.com/)
8	Four 4S Lipo batteries for powering the motors, with a capacity of 6000 mA for each battery (high-capacity batteries cannot be imported)
9	Telemetry
10	3S Lipo battery for powering the winch and the RPI
11	Raspberry PI 4 with 8 GB ram
12	A 6 Ampere UBEC (Universal Battery Elimination Circuit) to connect the RPI to the battery to convert the voltage from 11.4 V to 5 V
13	L298N H-Bridge board (to control the direction and speed of the winch)
14	Lever wire connectors

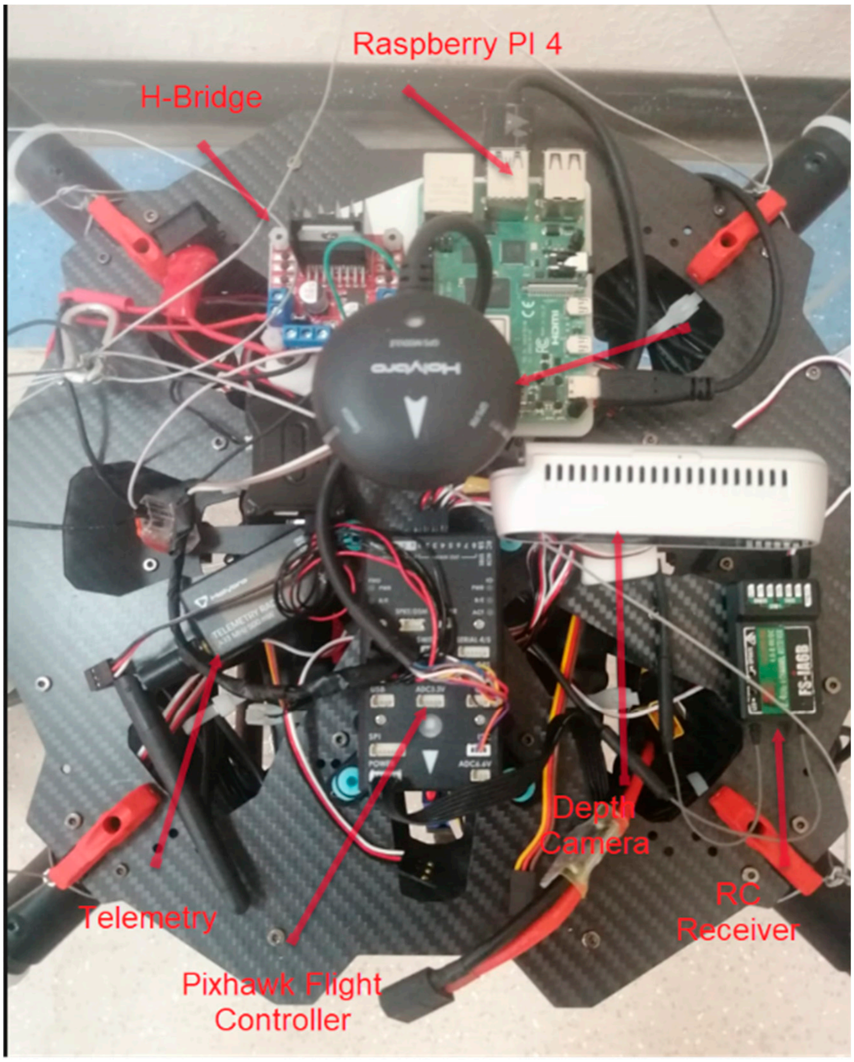


Figure 7. Top view of the designed quadrotor flying vehicle.

To facilitate the secure attachment of the depth camera to the quadrotor frame, a custom mounting solution is developed. This mounting design is meticulously created using 3D modeling software and subsequently realized through the 3D printing technique, employing ABS filament for construction. This approach ensures the precise integration of the depth camera into the quadrotor's structure, enhancing its overall functionality.

The motor-propeller combinations have been carefully selected to deliver the requisite thrust for quadrotor flight. A breakdown of the weights for the various quadrotor components is presented in Table 2.

Table 2. Weight of the quadrotor main components.

No	Component	Quantity	Weight/Item (Kg)	Weight (Kg)
1	Quadrotor (without batteries)	1	3.750	3.750
2	Robotic arm	1	2.464	2.464
3	Winch	1	0.750	0.750
4	4 S Lipo batteries	3	0.797	2.391
5	3S Lipo battery	1	0.349	0.349
	Total weight			9.704

The quadrotor, inclusive of the winch, robotic arm, and batteries, exhibits a total weight of 9.7 kg. The motors have been chosen to provide a maximum thrust of 13.44 kg at 100% throttle, and a total thrust of 9.72 kilograms at 75% throttle, as indicated in Table 3. It is noteworthy that during hover, the system operates within a throttle range of 50% to 80% to ensure continuous motor functionality, Table 3.

Table 3. KDE DC motor performance with Propeller 15.5″X5.3 [29].

No.	Throttle	Thrust (Kg)	Motor Speed (RPM)	Amperage (A)	Power (W)
1	25%	0.42	2120	1.5	19
2	37.5%	0.89	2920	4	52
3	50%	1.44	3640	8	104
4	62%	1.89	4240	13.6	178
5	75%	2.43	4780	20.2	264
6	87.5%	2.88	5200	27.9	365
7	100%	3.36	5680	36.9	483

While the current motor and propeller configuration proves suitable for the intended purposes of the design quadrotor, there is room for enhancement. Consideration may be given to upgrading to more powerful motors or adopting a hexacopter configuration for the Multirotor Flying Vehicle (MRFV) to potentially enhance its performance and capabilities.

Flight time estimation was conducted using the ecalc.ch website [30]. The analysis revealed that the quadrotor, with its existing batteries, can hover for approximately 7.6 min. This duration is relatively short due to the limited capacity of the current batteries. To extend the hover time, it is advisable to upgrade to higher-capacity batteries while also working on reducing the overall weight of the multirotor flying vehicle (MRFV). An alternative method for powering flying vehicles, particularly drones or other electric-powered aircraft, is to connect them to batteries housed on a small ground vehicle via wired connections. This approach allows the flying vehicle to draw energy from a ground-based power source, significantly extending flight duration by eliminating the need for heavy onboard batteries. By relocating the batteries to the ground vehicle, the quadrotor benefits from reduced weight, which not only optimizes performance but also improves stability and maneuverability. This configuration enhances operational efficiency, especially in applications like date harvesting, where longer flight times are crucial for productivity. Additionally, the ground vehicles can easily navigate fixed locations, ensuring a continuous power supply without restricting the quadrotor's mobility.

The system's control is achieved through two Raspberry Pi companion computers, accessible via an Android app. The first Raspberry Pi is securely mounted on the arm and serves to govern the operation of the saw, linear actuator, and end effector. Meanwhile, the second Raspberry Pi is affixed to the quadrotor and handles tasks such as winch control and video stream capture from the depth camera. Each Raspberry Pi is capable of capturing video streams from two cameras, including depth and USB cameras. This dual Raspberry Pi setup enhances the system's versatility and control capabilities.

2.4. RPI Connections

The control of the system can be done through two Raspberry PI companion computers through the Android application. The first RPI is fixed on the arm and it is used to control the saw, the linear actuator, and the end effector, Figure 8. The second RPI is fixed on the quadrotor and it can control the winch and capture the video stream of the depth camera, Figure 9. Each RPI can capture the video streams of two cameras, depth, and USB.

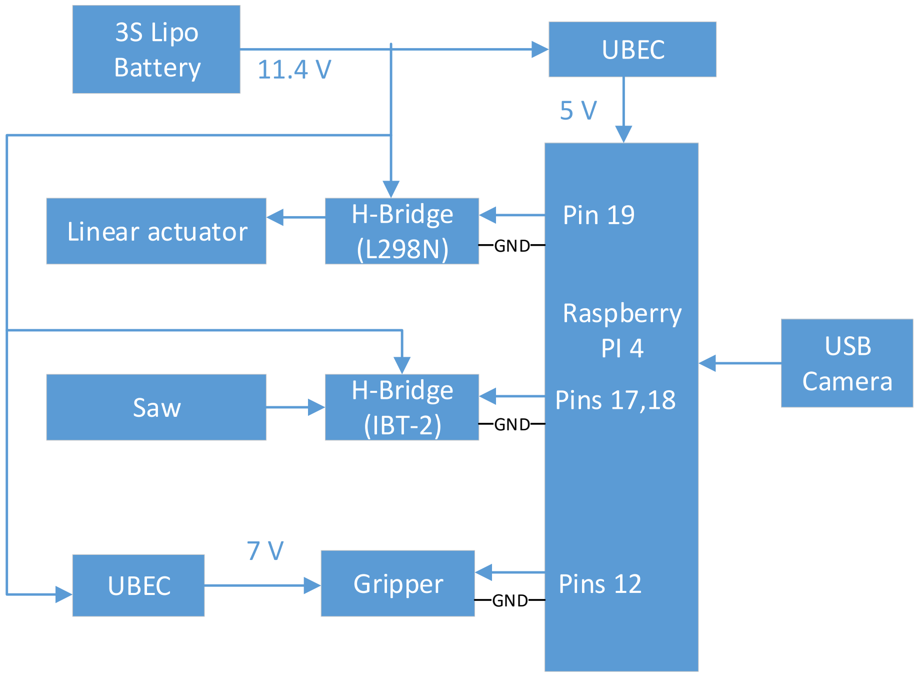


Figure 8. Connections of the RPI fixed on the robotic arm.

2.5. Control Software

To facilitate remote system control and real-time monitoring of the quadcopter's motion and cutting process, a software program has been developed. This system comprises two essential components: a server installed on the Raspberry Pi boards and an Android application, which can be installed on handheld devices such as mobile phones or tablets. The server is constructed using the Python programming language, while the Android application is created using Android Studio software (2022.3.1), as detailed in [31].

The application establishes a connection with the two companion computers via local Wi-Fi, providing seamless communication. Moreover, it is worth noting that the system can be adapted to enable connections through the Internet, thereby allowing the operation of the system from virtually any location.

A screenshot of the application's main screen is shown in Figure 10. Within the application, users can manipulate the winch and the robotic arm components (saw, linear actuator, and end effector) through intuitive sliders. Furthermore, the application receives and records video streams from two cameras, with one of them potentially serving as a depth camera. The quadcopter itself can be controlled via a remote controller (RC), granting users full command over its flight. This comprehensive software system significantly enhances the versatility and usability of the MRFV for date palm harvesting.

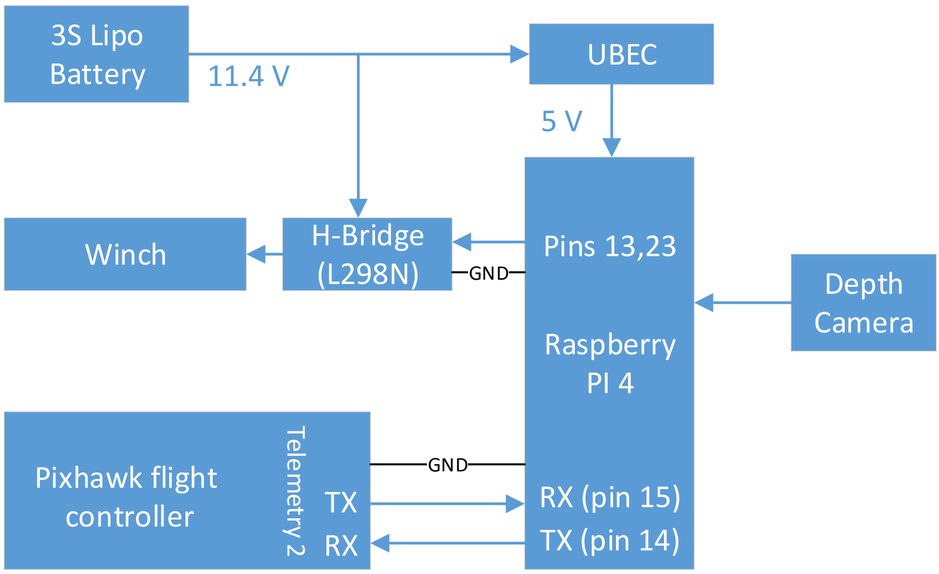


Figure 9. Connections of the RPI fixed on the quadrotor.

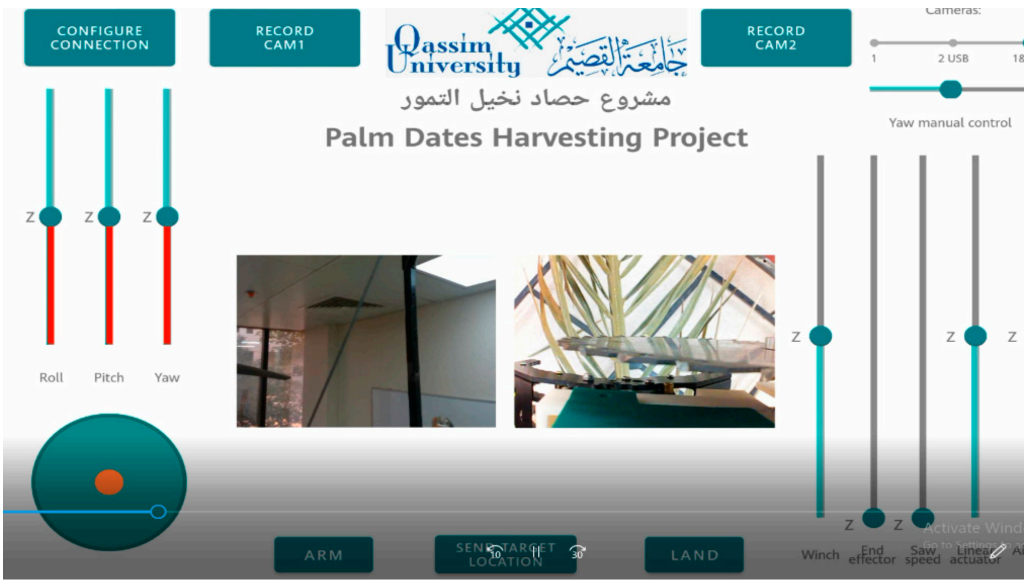


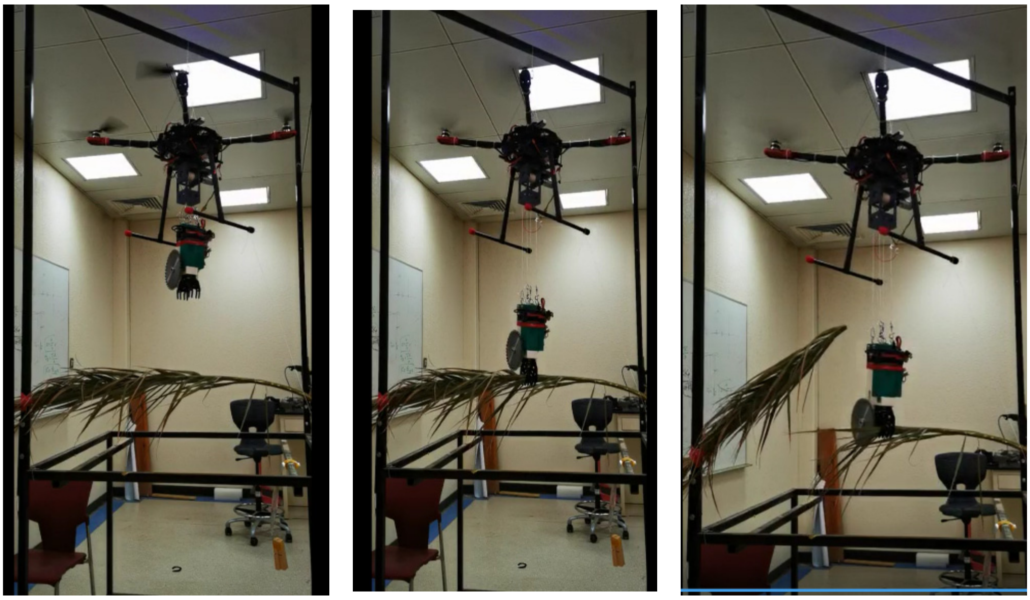
Figure 10. Screenshot of the application main screen during the operation.

3. Testing

The testing phase was executed with resounding success within our laboratory, employing a dedicated testbed. The branch-cutting process was carried out flawlessly, with all components of the system functioning seamlessly. Multiple video recordings were captured from various perspectives to document the experiment. The experiment procedure can be summarized as follows:

- The quadrotor, equipped with the winch and robotic arm, was suspended on the testbed using a single wire, as shown in Figure 11.
- The quadrotor was armed via the remote controller, and the throttle was progressively increased to achieve the desired hover condition.
- The application was initiated and seamlessly connected to the two Raspberry Pi servers.

- The winch slider was skillfully adjusted to lower the winch until it reached the target branch.
- The gripper slider was utilized to precisely close the gripper, securely grasping the branch. Subsequently, the winch was raised slightly to optimize the grip.
- The saw slider was adjusted to elevate the speed of the saw to its optimal level.
- The linear actuator slider was employed to activate the actuator, thereby propelling the saw forward with precision to execute the cutting process.



Before operating the winch After operating the winch After completing the cutting

Figure 11. Testing the system in the lab using the testbed.

Throughout this procedure, the USB video stream plays a vital role in guiding the gripper and providing real-time monitoring of the cutting process. Following the successful completion of the cutting operation, the quadrotor is promptly disarmed.

It is worth mentioning that the depth camera serves the purpose of guiding the quadrotor to the precise location of the palm trees during outdoor flights, enhancing navigational accuracy. Moreover, video streams from both cameras can be recorded on the tablet for subsequent post-processing and analysis. While the Android application is designed to arm, operate, and land the quadrotor, this functionality has been verified using the hardware-in-loop technique (HILT).

4. Quadrotor Performance

The performance of the quadrotor during the cutting process is assessed through data extracted from the log files stored in the Pixhawk flight controller. The attitude and altitude angles, as shown in Figures 12–15, reveal only minimal variations throughout the operation. These minor deviations demonstrate that the system is able to maintain a stable orientation, which is crucial for ensuring precise control during the cutting process. The stability of the quadrotor is further confirmed by the velocity data, which fluctuates around zero with minimal magnitude. This indicates that the quadrotor experiences only slight oscillations, highlighting its ability to maintain steady flight despite the complexities of the task.

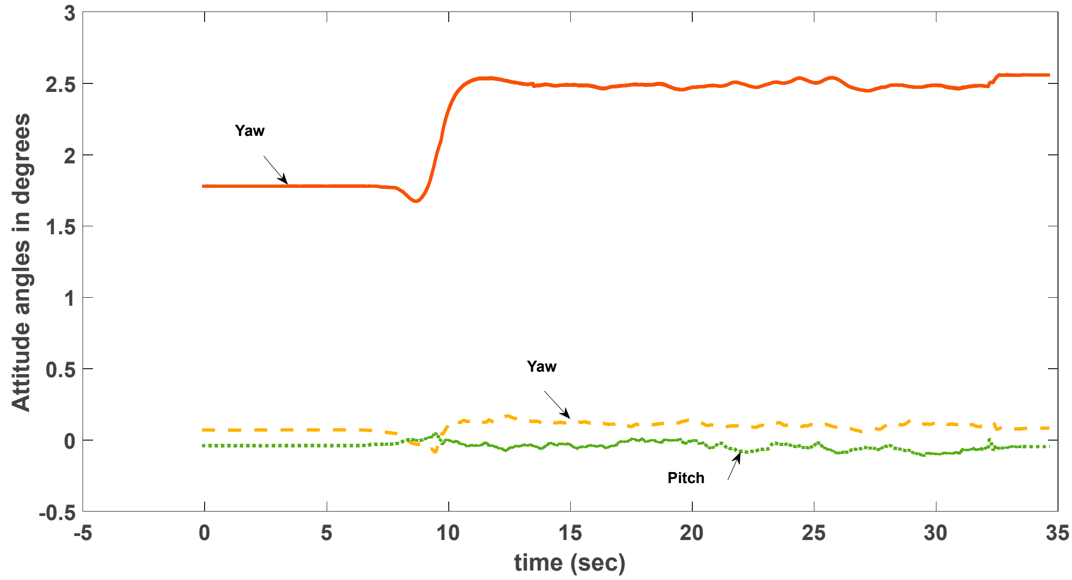


Figure 12. Quadrotor attitude angles.

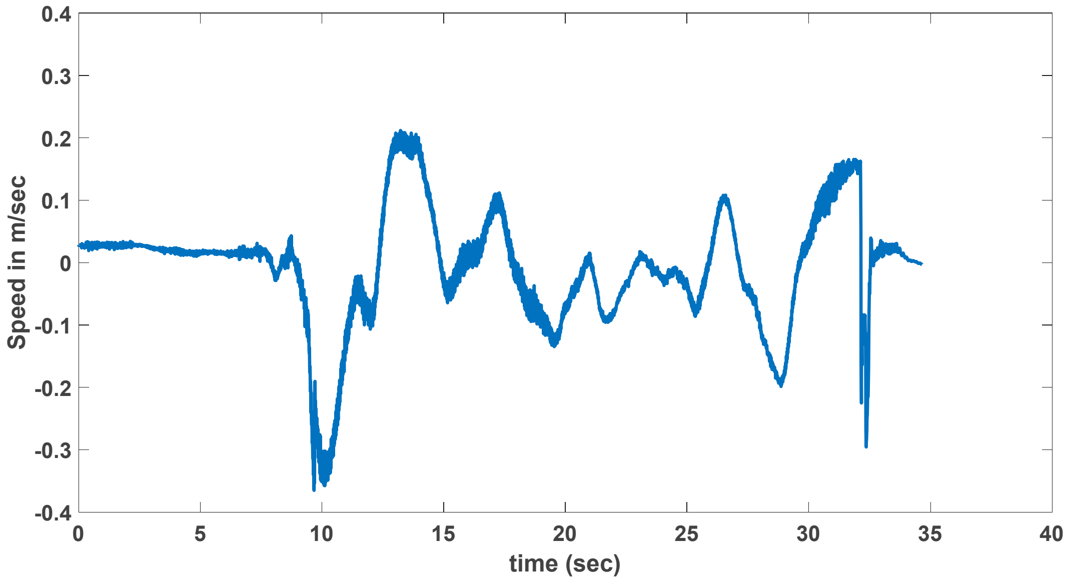


Figure 13. Quadrotor speed in the longitudinal direction.

These small fluctuations in both attitude and velocity remain well within acceptable limits, particularly for precision tasks like branch cutting, where even slight movements can impact the outcome. The system's ability to control such minor variations is key to achieving a smooth and precise operation. The minimal deviation in orientation and velocity ensures that the quadrotor remains stable, thus allowing the cutting task to proceed with minimal interference.

The robotic arm plays a crucial role in maintaining this stability, as it stabilizes the branch during the cutting process. Even with the slight movements of the quadrotor, the arm's firm grip on the branch prevents misalignment, vibrations, or other disturbances that could compromise the precision of the cut. The arm's stabilization function is particularly important in mitigating the impact of minor perturbations from the quadrotor's movement, ensuring that the branch remains steady and accurately positioned.

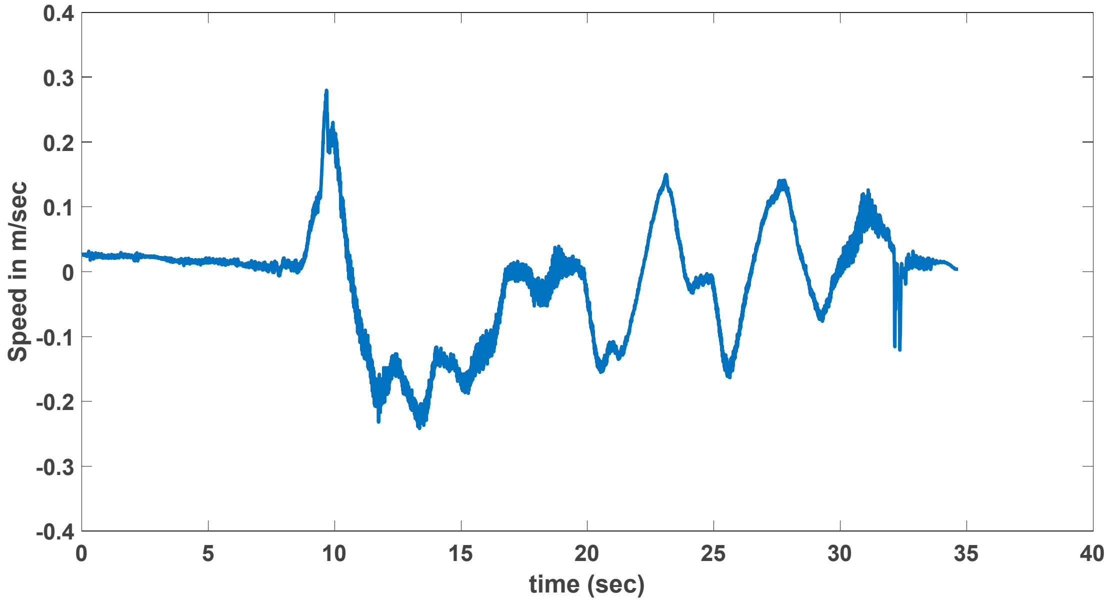


Figure 14. Quadrotor speed in the lateral direction.

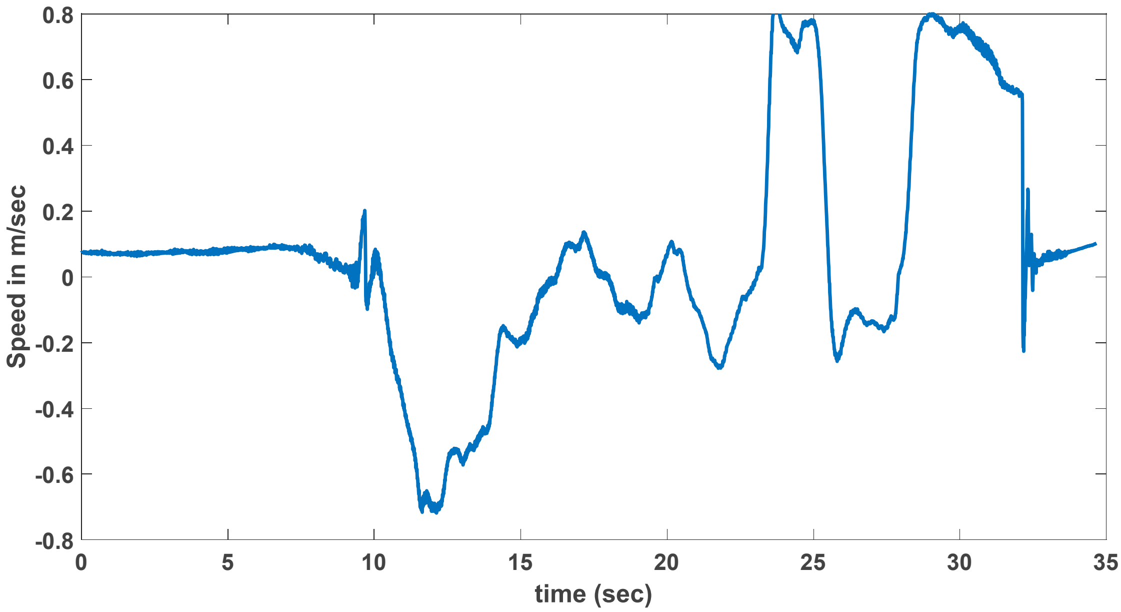


Figure 15. Quadrotor speed in the vertical direction.

The synergy between the quadrotor's controlled movements and the robotic arm's stabilizing mechanism contributes significantly to the overall success of the cutting operation. Despite the minor oscillations in the quadrotor's posture and velocity, the robotic arm ensures that the branch remains securely in place, preventing misalignment during the cutting process. This coordination between the quadrotor and the arm demonstrates the system's capacity to perform delicate tasks with high accuracy, even in the presence of minor perturbations. The ability to maintain this level of precision under such conditions highlights the robustness and effectiveness of the system, making it suitable for tasks requiring fine control and stability.

5. Conclusions

A novel system has been developed to revolutionize the process of date palm harvesting by leveraging the advanced capabilities of multirotor flying vehicles (MRFVs). This innovative system offers a remote, aerial solution, eliminating traditional challenges such as the need for manual tree climbing or reliance on ground-based machinery. By incorporating cutting-edge technology, this system represents a significant leap forward in agricultural automation, enhancing both the safety and efficiency of harvesting operations.

The system's design and engineering have been carefully executed, with extensive manufacturing and testing conducted under controlled laboratory conditions. The results from these tests demonstrate the system's ability to perform precision cuts on date branches with minimal disruptions. The quadrotor maintains a stable attitude and altitude control, showing only minor perturbations in its angles and velocity. These small movements do not interfere with the cutting process, as the robotic arm securely grips and stabilizes the branches during cutting operations. This stability highlights the potential of MRFVs to perform intricate tasks, even in complex environments like date palm plantations.

In its current configuration, the system is primarily focused on the accurate and efficient cutting of date branches. However, this is only the beginning of what can be achieved. The next logical step involves expanding the system's capabilities to include the transport of harvested branches. Given that date branches can weigh upwards of 40 kg, this will require the development of a more powerful and robust heavy-load MRFV that can handle such payloads while maintaining the same precision and control demonstrated in the cutting process.

6. Recommendations

To fully realize the potential of this system and transform date palm harvesting on a large scale, the following recommendations are proposed:

1. Development of a Heavy-Load Multirotor Flying Vehicle (MRFV):

The current system is adept at precision cutting, but to extend its functionality to transporting harvested branches, a more powerful MRFV is essential. Future iterations should focus on designing an MRFV capable of carrying payloads exceeding 40 kg while ensuring stability and control during flight. The addition of payload-lifting capabilities will allow the system to transition from just cutting branches to also transporting them to collection points, thereby increasing operational efficiency. A modular design could also be explored to allow the MRFV to switch between cutting and carrying modes.

2. Full Autonomy and Advanced Navigation:

To maximize efficiency and minimize human intervention, the system should evolve towards full autonomy. This entails developing sophisticated algorithms that enable the MRFV to autonomously take off, navigate to predefined locations, and engage in precise cutting actions. Autonomous navigation should incorporate advanced GPS, vision-based systems, and possibly LiDAR to identify individual trees and locate optimal cutting positions. Additionally, the system must be able to avoid obstacles and adjust to dynamic environmental factors, such as wind or unexpected obstructions. Once branches are cut, the MRFV should autonomously transport them to a designated collection area, completing the entire harvesting cycle without human input.

3. Integration of a Multi-Unit System for Large-Scale Harvesting:

For large date palm plantations, the development of a coordinated, multi-unit MRFV system should be considered. Multiple MRFVs working in tandem, either autonomously or semi-autonomously, could drastically reduce the time and labor required for harvesting. The system could be integrated with centralized control software, where multiple MRFVs are assigned to different sectors of a farm. This would allow for simultaneous harvesting across large areas, significantly increasing productivity. Each unit could be programmed to communicate with others to avoid collisions and ensure an efficient division of labor.

4. Sustainability and Energy Efficiency Considerations:

As this system moves towards field deployment, attention must be given to its energy consumption and sustainability. The MRFV's power requirements, especially when carrying heavy loads, could become a limiting factor. Future designs should explore the use of more efficient propulsion systems, lightweight materials, and potentially renewable energy sources such as solar panels to extend flight duration. Battery technology should also be improved to ensure the system can operate for extended periods in the field without frequent recharging.

By addressing these recommendations, the future of date palm harvesting could be dramatically transformed. A fully autonomous, efficient, and scalable system has the potential to revolutionize agricultural practices, reducing labor costs, improving safety, and significantly enhancing productivity. The successful integration of such systems into farming practices could pave the way for similar advancements in other areas of agriculture, leading to broader applications of aerial robotics in crop management, harvesting, and transportation.

7. Patent

A patent titled 'Unmanned Aircraft for Harvesting Dates' (No. SA15595) was issued by the Saudi Authority for Intellectual Property, Saudi Arabia, on 1 April 2024.

Author Contributions: Methodology, H.M.O. and S.M.S.M.; Software, H.M.O.; Validation, H.M.O. and S.M.S.M.; Formal analysis, H.M.O.; Investigation, H.M.O. and S.M.S.M.; Writing—original draft, H.M.O. and S.M.S.M.; Writing—review & editing, H.M.O. and S.M.S.M.; Supervision, H.M.O.; Project administration, H.M.O. All authors have read and agreed to the published version of the manuscript.

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