VOLUME 16, N° 4 2022
Journal of Automation, Mobile Robotics and Intelligent Systems

Design of a Vision-Based Autonomous Turret

Submitted: 10th January 2023; accepted: 10th February 2023

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DOI: 10.14313/JAMRIS/4-2022/35

Abstract:
This article describes the hardware and software design of a vision-based autonomous turret system. A two degree of freedom (2 DOF) turret platform is designed to carry a cannon equipped with an embedded camera and actuated by stepper motors or direct current motors. The turret system includes a central calculator running a visual detection and tracking solution, and a microcontroller, responsible for actuators control. The Tracking-Learning-Detection (TLD) algorithm is implemented for target detection and tracking. Furthermore, a Kalman filter algorithm is implemented to continue the tracking in case of occlusion. The performances of the designed turret, regarding response time, accuracy and the execution time of its main tasks, are evaluated. In addition, an experimental scenario was performed for real-time autonomous detection and tracking of a moving target.

Keywords: *Autonomous turret, Stepper motor, DC motor, Vision based control, Tracking-Learning-Detection (TLD) algorithm, Kalman based visual tracking*

1. Introduction

Autonomous weapon systems (AWSs) have become decisive on the battle ield because they can effectively carry out various missions such as surveillance, intelligence, reconnaissance, and armed operations, without engaging human lives [2].

Turrets and sentries are widely used on the bat-tle ields. Making these systems autonomous will allow surveillance, detection, identi ication, tracking, and even destruction of potential targets without human intervention.

Aware of their interests, the defense sector and the military industry paid particular attention to autonomous turret systems, which resulted in the development, commercialization, and extensiveuse of these systems. The bestknown example of commercial autonomous turret systems is the Samsung SGR-A1 [2], which is an autonomous surveillance gun developed by Samsung Techwin to assist South Korean troops in the Korean demilitarized zone. This system has capabilities for surveillance, detection, tracking, and iring, as well as voice recognition [2].

In contrast, review of academic literature shows that the number of works carried out for the development of autonomous turret systems remains lim-ited. P. Demski et al. [?] proposed a remote-controlled turret system with video transmission. M. Tsourma and M. Dasygenis [6] described a system that supports motion detection, tracking, and face recognition. S. Kuswadi et al. [5] designed and realized an auto-matic turret system that includes a camera and a PID controller to drive pitch and yaw motion of the turret. R. R. Alcala et al. [1] designed and implemented a body wearable device to control a sentry gun turret.

This paper describes the full design of an autonomous turret system controlled using a visual ser-voing solution. This system can operate in manual or automatic mode. In manual mode, the operator controls the pan and tilt of the turret from a remote interface. The camera embedded on the turret allows surveillance of an area of interest in real-time. In automatic mode, a Tracking Learning Detection (TLD) algorithm [3] is implemented for target detection and recovering. In this case, the turret detects and tracks autonomously the target selected by the operator. A Kalman ilter [4] is implemented to predict and track the target position in real-time using TLD observation.

The remainder of the paper is organized as follows. Sections 2 and 3 describe, respectively, the hardware and software design of the turret system. Section 4 is devoted to the evaluation of the designed turret performances, regarding dynamic and real-time metrics.

2. Hardware Design

The hardware architecture of the vision-based autonomous turret is shown in Fig. 1. The central calculator manages the manual and as well as the vision-based automatic control. A manual control interface (joystick, keyboard, or mouse) can be connected to this computer via USB. This computer also executes automatic target detection and tracking using the video stream received from the camera embedded on the gun. It then computes and sends the highlevel commands to the microcontroller via an USB interface. The microcontroller is responsible for the lowlevel control of the turret actuators by outputting the appropriate PWM signals to control the power stage. The latter generates the power signals that drive the pan and tilt actuators.

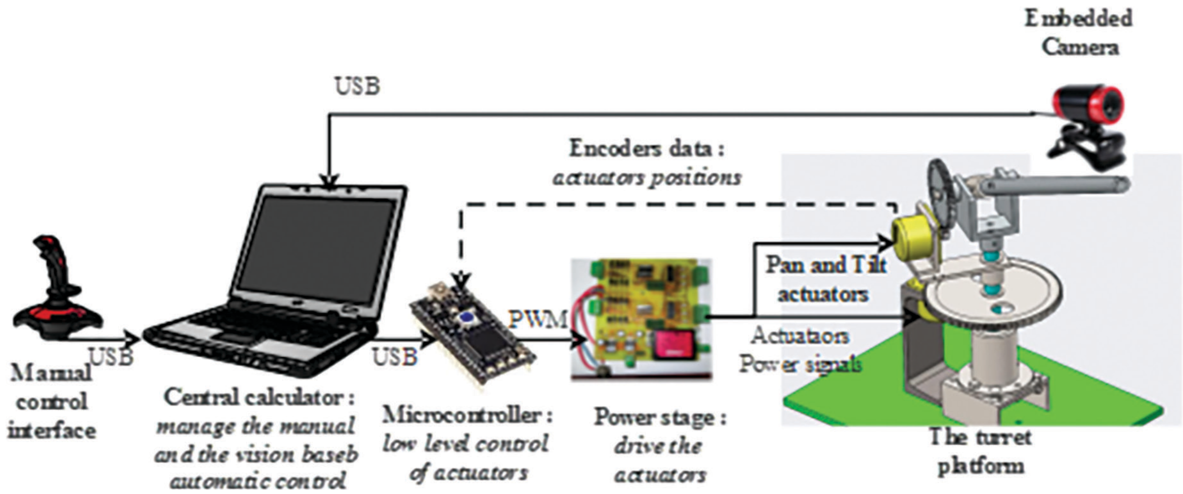


Fig. 1. Hardware architecture of the vision based autonomous turret

In the following subsections, we will explain each component of the turret system.

2.1. The turret platform

Fig. 2 shows the mechanical structure of the turret platform, which can perform pan and tilt rotations, using two motors. The working volume of this turret is a halfsphere, since the pan de lection can vary from 0° to 360°, while the tilt can take any value from 0° to 180°. The motion transmission is performed using parallel gears, which allow speed reduction and torque multiplication. The pan and tilt reduction ratios are 1/10 and 1/5, respectively. The pan rotation is ensured by a tapered roller bearing, which can support relatively large radial and axial loads.

2.2. Actuators and power stages

We built two versions of the turret platform: the irst is driven by stepper motors, while the second is driven by DC motors. Characteristics of the used actuators are given in Table 1. On the one hand, the stepper motors do not require a position control loop; however, besides having low speed and low torque compared to DC motors, their torque also decreases rapidly as the speed increases. On the other hand, DC motors deliver higher speed and higher torque but require a position control loop. We used a POLOLU 70:1 DC motor that integrates an incremental encoder, which allows the implementation of a position control loop.

To drive the stepper motors, we realized the power stage shown in Fig. 3, which is based on the L297 and L298 integrated circuits. To drive the DC motors, we designed a power stage using mainly the L293 integrated circuit as shown in Fig. 4. To protect the microcontroller, a galvanic isolation is introduced using the integrated circuit ULN2803a. Furthermore, an amplication stage based on two BDW93C transistors is used to supply the DC motors.

2.3. Microcontroller

To perform the low-level control of the actuators, we used the MBED NXP LPC1768 microcontroller, which is a rapid prototyping module based on an ARM7 processor.

Fig. 2. The turret platform

Tab. 1. Actuators of the turret platform

Turret version	Version 1	Version 2
Actuators	***Stepper motors :***	***DC motors :***
	SUPERIOR	
	ELECTRONIC	POLOLU 70:1
	M061-LS02	
Actuators characteristics	Voltage : 5 V	Voltage : 12 V
	Current : 1 A	Current : 5 A
	Torque : 0.53 N.m	Torque : 1.37 N.m
	Resolution : 1.8°	Encoder
		resolution : 0.16°

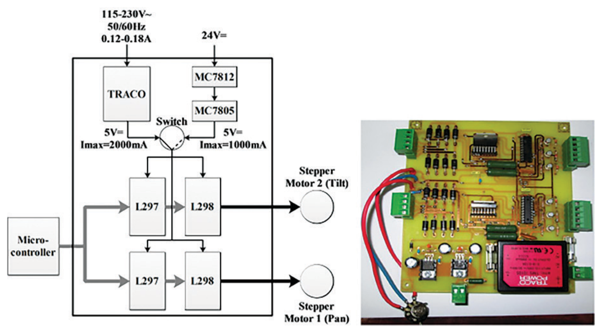


Fig. 3. Power stage of stepper motors

2.4. Embedded camera

A video camera connected to the central computer via a USB link is mounted on the cannon (the gun). Aligning the center of the image with the center of the target allows aiming at the object of interest. The size of the image is 640 × 480 pixels, which means the center of the image is located at $X_0 = [U_0 = 320, V_0 = 240]^T$ pixels.

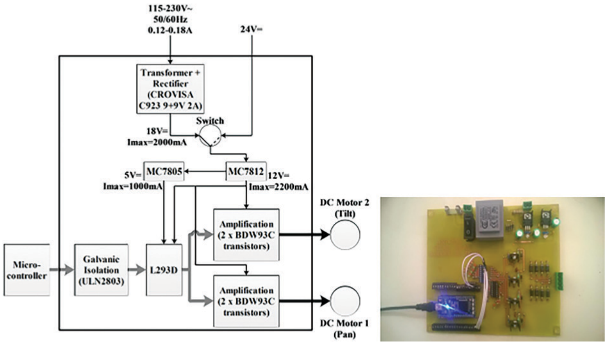


Fig. 4 . Power stage of DC motors

3. Software Design

In addition to the manual control, the designed system implements a vision-based autonomous mode for target detection and tracking. For detection, we used Tracking-Learning-Detection (TLD) algorithm [3]. In addition, we designed a Kalman-based vision algorithm for target tracking to ensure an optimal estimation of the target position, even when it becomes completely occluded [4]. Furthermore, we proposed control laws that drive the actuators of the turret for real-time tracking of the target.

3.1. Detection method based on TLD algorithm

The Tracking-Learning-Detection (TLD) method proposed by Zdenek Kalal, performs tracking of unknown objects in a video stream [3]. The main steps of the TLD method are shown in Fig. 5. Initially, the object of interest is selected manually and then the TLD method tracks the target by learning its appearance. The recursive tracker and the detector run in parallel and their results are merged, then validation and learning steps are performed to improve detection performance by identifying and updating errors in each frame.

The described detection methods locate the target at a given point in time, without predicting the target motion. The time taken to transmit the target coordinates to the turret is signi icant. This is particularly worrying for fast dynamic targets. To ensure real-time tracking, a prediction step using an algorithm based on a Kalman ilter was added to the design.

3.2. Tracking

To ensure target tracking, we implemented an algorithm based on the Kalman ilter [4], as represented by the low chart in Fig. 6.

The tracking problem is modeled by (1), which includes the target dynamics and the observation equa-tion, where $X = [x, y]^T$ is the target position; $\Delta = [\delta x, \delta y]^T$ is the target velocity; $Z = [U, V]^T$ is the observed position of the target obtained by the detection algorithm; *A, B,* and C are, respectively, the evolution, the control, and the observation matrix; *Te* is the sample period; and *W* and *V* are, respectively, the state and the measurement noises. It should be noticed that the target is assumed to evolve at a constant speed $\delta x, \delta y = Cte$.

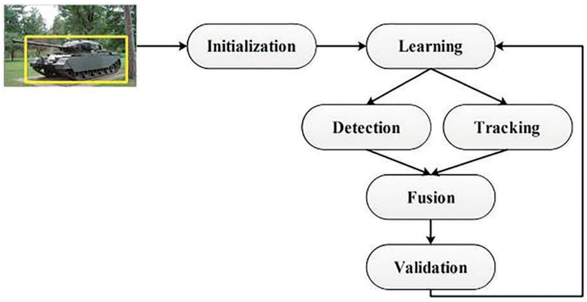


Fig. 5 . TLD algorithm

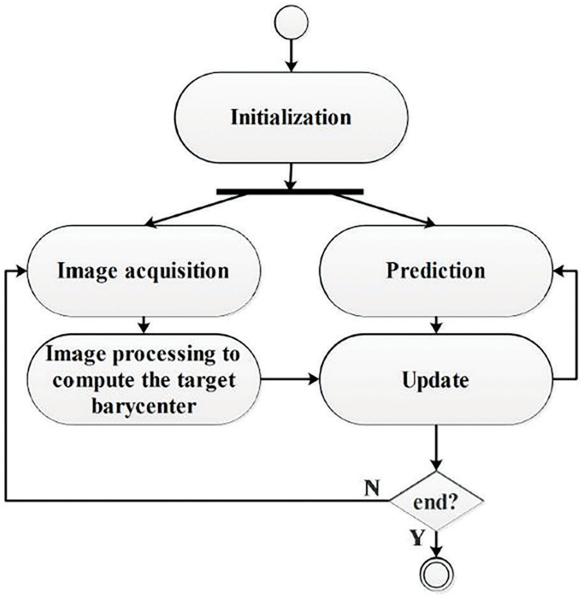


Fig. 6 . Tracking algorithm

$$\begin{cases} X(k) = A \cdot X(k-1) + B \cdot \Delta + W(k) \\ Z(k) = C \cdot X(k) + V(k) \end{cases}$$
$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; \; B = \begin{pmatrix} T_e & 0 \\ 0 & T_e \end{pmatrix}; \; C = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{1}$$

The Kalman ilter prediction step is performed according to (2), where P_p and P are the covariance matrix of the prediction and measurement update error, and Q is the covariance matrix of the process noise.

$$\begin{cases} X_p(k) = A \cdot X(k) + B \cdot U \\ P_p(k) = A \cdot P(k-1) \cdot A^T + B \cdot Q \cdot B^T \end{cases} \tag{2}$$

The update step is performed according to (3), where R is the measurement noise covariance matrix and K is the Kalman gain.

$$\begin{cases} K(k) = P_p(k) \cdot C \cdot \left[C \cdot P_p(k) \cdot C^T + R \right] \\ P(k) = P_p(k) - K(k) \cdot C \cdot P_p(k) \\ X(k) = X_p(k) + K(k) \cdot \left[Z(k) - C \cdot X_p(k) \right] \end{cases} \tag{3}$$

To validate the tracking system, the target is hidden for an interval of time. The tracking results

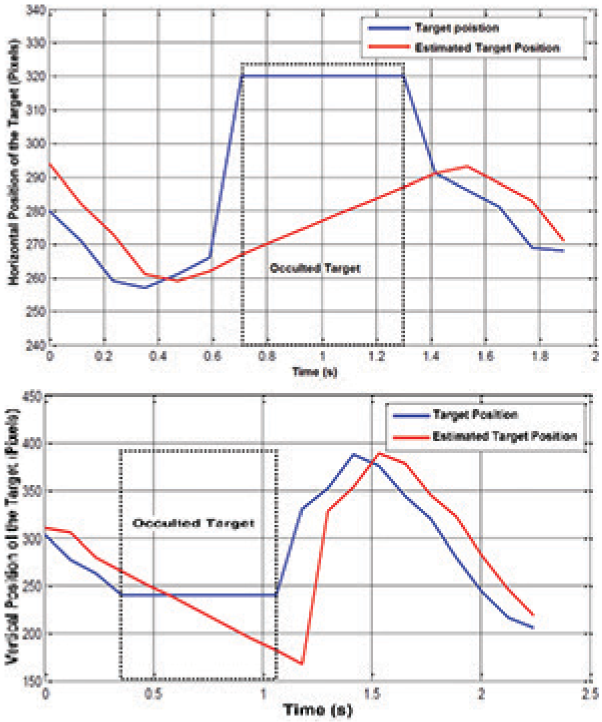


Fig. 7. Target tracking by the Kalman filter

are shown in Fig. 7. When the target disappears from the camera's ield of view, the detection algorithm provides the coordinates of the center of the image, i.e., 320 pixels for the horizontal position and 240 pixels for the vertical position. In this case, the Kalman ilter ensures tracking continuity through the prediction model.

3.3. Control

The control law implemented on the microcontroller aims to line up the center of the image $X_0 = [U_0, V_0]^T$ with the center of the target $X = [U, V]^T$, by controlling the actuators of the turret platform. To avoid the phenomenon of pumping (oscillation), the center of the image is not a single pixel but an area defined by $X_0 = [U_0 + \delta_u; V_0 + \delta_v]^T$. In our case, we set $\delta u = \delta v = 32$ pixels.

Fig. 8 and Fig. 9 show the control lowcharts for stepper and DC motors, respectively. Note that the stepper motors' control law is "All-or-None" type, while the DC motors' control law is "Proportional" type. In 8, F_u and F_v are the frequencies supplied to the turret pan and tilt stepper motors, while in 9 $Rate_v$ and $Rate_u$ are the duty cycles supplied to the turret pan and tilt DC motors.

3.4. Graphical User Interface

We designed a graphical user interface (GUI) for the turret system according to the state machine diagram shown in Fig. 10, and implemented it using MATLAB GUI editor. The GUI allows the operator to visualize the scene captured by the camera and to manually control the turret in order to look for a possible target. After selecting a target, it is possible to start the automatic tracking.

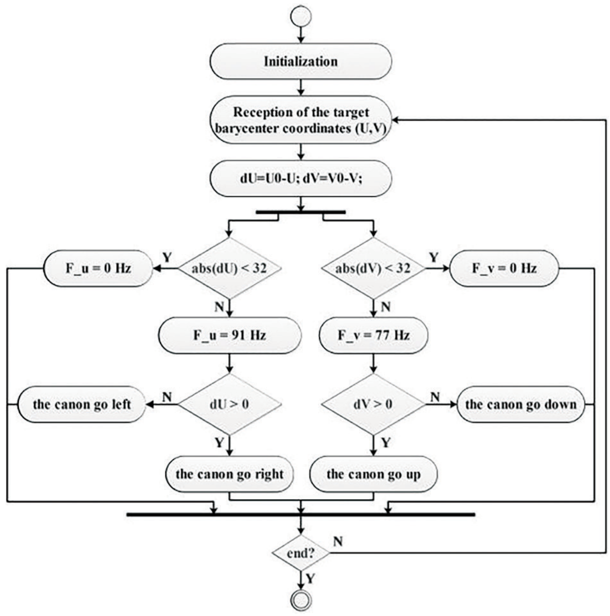


Fig. 8. Stepper motors control flowchart

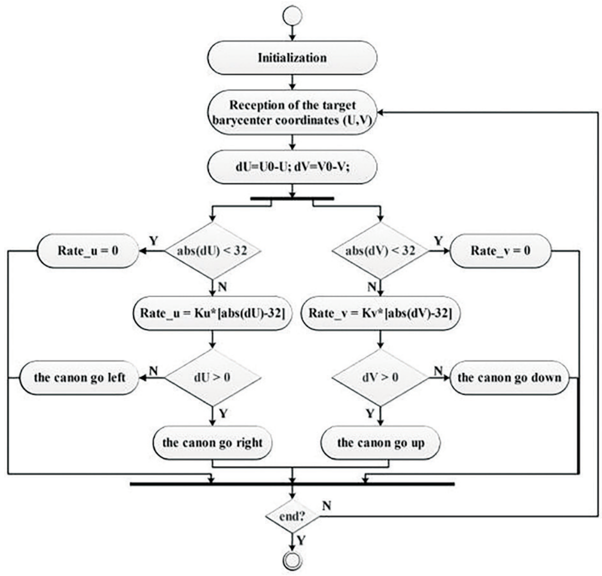


Fig. 9. DC motors control flowchart

4. Results and Discussion

4.1. Dynamic Performances Evaluation

We studied the dynamic performance, in terms of speed and accuracy, of the two versions of the turret (based on stepper and DC motors). We designed the experimental setup depicted in Fig. 11. It consists in tracking a red virtual target and performing de ined trajectories. This target is created and animated virtually using the simulation softwareMATLABand a data-show projector.

The defined trajectories of the target are: *i)* horizontal and vertical rectilinear motion (see Fig. 12a); *ii)* horizontal and vertical sinusoidal motion (see Fig. 12b); and *iii)* coupled horizontal-vertical motion by tracing the in inite shape (see Fig. 12c and Fig. 12d).

The different tests provided the results given in Table 2. These results show that the response time of

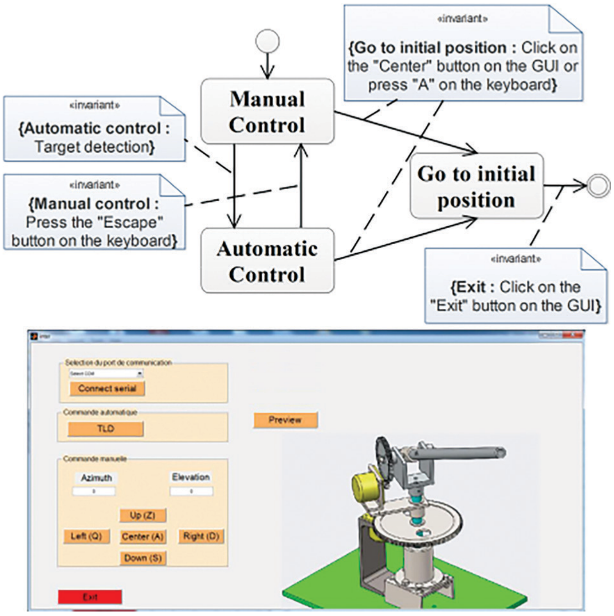
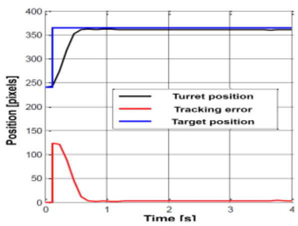
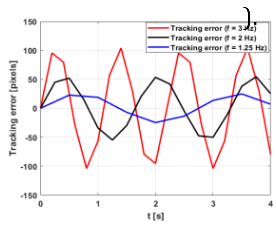


Fig. 10. Graphical User Interface

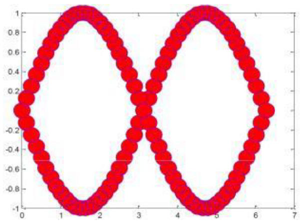
Fig. 11. Experimental setup to evaluate the turret dynamic performances



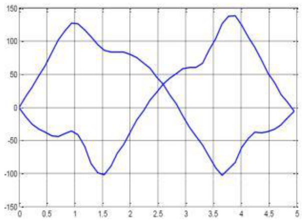
(a) Rectilinear motion.



(b) Sinusoidal motion.



(c) Infinite shape motion of the target.



(d) Infinite shape motion of the turret.

Fig. 12. Target trajectories to evaluate the turret dynamic performances

the horizontal axis is greater than that of the vertical axis because the horizontal axis requires more torque. The results also show that the DC motor is faster than the stepper motor. However, it should be kept in mind that the DC motor requires a position sensor and a control loop, while the stepper motor is controlled

Tab. 2. Dynamic performances evaluation of the turret

	Stepper motors based turret		DC motors based turret	
	Pan axis	Tilt axis	Pan axis	Tilt axis
Response time	1.880 s	0.826 s	0.59 s	0.472 s
Static error	8 pixels	22 pixels	4 pixels	3 pixels

Fig. 13. Real-time tracking of a moving target

in an open loop. In terms of accuracy, both versions of the turret have satisfactory accuracy because the measured static errors are in the dead zone [δu, δv] = [32, 32] pixels.

4.2. Functional validation

The functional testing of the system is performed through real-time tracking of a moving target. The user manually controls the turret to search for a potential target. As shown in picture 2 of Fig. 13, selecting the mobile robot as a target starts the automatic tracking. This is successfully accomplished despite a partial occlusion of the target, as shown in picture 4 of Fig. 13.

4.3. Real-time performances evaluation

To evaluate the real-time performances of the system, we measured the execution time of its main tasks over a number of iterations. We used as a central calculator a Fujitsu Lifebook laptop with a CORE i5 processor and 2.67 GHz of RAM.

The results of this study are summarized in Table 3. The Worst-Case Execution Time (WCET) is 147.1 ms, which is equivalent to the processing of more than 6 frames/second. The computing time is consumed mainly by the TLD and the display tasks. The execution time standard deviation is less than 1 ms, which quanti ies the temporal stability of the system.

Tab. 3. Temporal Analysis of the System's Tasks

Tasks Vs. Execution Time [ms]	Max	Min	Mean	std*
TLD + Display	145.1	63.0	77.70	0.216
Computing the target barycenter coordinates	0.3	0.1	0.13	0.003
Sending coordinates to the microcontroller	1.7	0.6	0.99	0.002
Standard deviation	147.1	63.7	78.82	0.221

5. Conclusion

This paper presents the hardware and software design of a vision-based autonomous turret system. Two versions of the turret platform were built: the first is actuated by stepper motors, while the second is actuated by Direct Current (DC) motors.

For real-time target detection, the TLD algorithms were implemented. For better target tracking, a prediction solution based on the Kalman ilter was added to the software architecture. The low-level control of the turret platform is ensured by a microcontroller, which implements control laws according to the used actuators.

Furthermore, functional and real-time performances of the system were studied. In addition, we validated the designed turret system through the case of tracking a moving target.

It can be concluded that the designed system based on the TLD method performs robust and real-time tracking. Moreover, this system does not need prior knowledge about the shape or the color of the target to accomplish the tracking. As future work, we will consider the case of multiple target classiication and tracking.

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