Technical Design Report of Matsya 6C, Autonomous Underwater Vehicle

Aditya H, Shubham T, Ruchir C, Mundhra S, Tejas B, Ayushi G, Parvik D, Govind S, Kalp V, Sankalp B, Lyric K, Kaustubh C, Advait R, Pratik S, Shivam A, Nandini K, Sanya A, Anuj B, Anurag D, Kaushik C, Mayank B, Archit S, Nimish S, Pranav J, Yashas S, Aaryan D, Archit G, Sameer M, Tanvi P, Shumail M, Suyash W, Adwai K, Akshaj A, Dhruvi M, Sparsh B, Urvi G, Anirudh J, Anshu A, Ayush P, Dey S, Siddhi D, Gokul R, Nishant B, Swapnil B, Verma K, Yash S, Atharva M, Karthik V, Rahul G, Shivam A, Shubhi A

Faculty Advisors: Prof. Leena Vachhani and Prof. Hemendra Arya

***Abstract*—Matsya is a series of Autonomous Underwater Vehicles (AUVs) being developed at the Indian Institute of Technology (IIT) Bombay to deliver a research platform in underwater robotics and promote autonomous systems. This paper presents an insight into the team's design process for the latest autonomous vehicle, *Matsya 6C*, and the analytical methods that the team used for the prototyping and development of the vehicle, including structural simulations, hydrodynamics analysis, underwater data transmission models, path planners and strategies to optimize the design. Significant architectural changes have been made to the subsystems to enable real-time handling of tasks. The vehicle was tested extensively to improve the reliability of existing features. Some key additions include improved heat dissipation, the simulation of an underwater localization system, and revamped controls and path planning.**

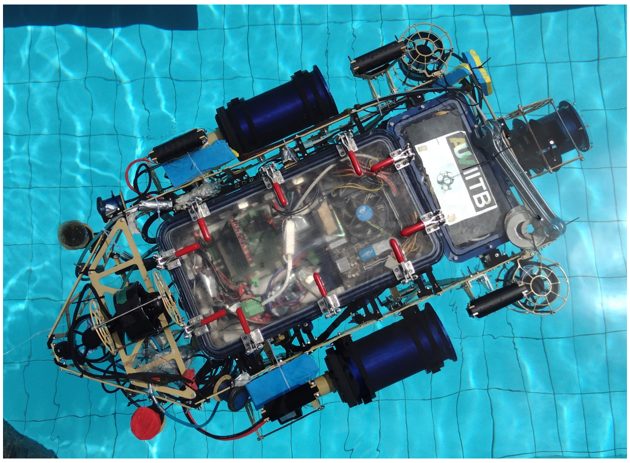

Figure 1: Matsya 6C

I. Competition Strategy

As we're headed back to San Diego after a long spell, RoboSub 2023 poses new hurdles to overcome. We have a simple yet effective strategy in mind – focusing on reliability as we return to the murky waters of TRANSDEC.

We plan to use YoloV5 for vision and decide between Earth and Abydos based on testing results. We also plan on staying with our destination for the remainder of the tasks for bonus points. Matsya 6C is fully equipped with all the necessities to complete every task. Hence, given the time constraints, we plan to complete the highest-scoring tasks to maximize our score. Having encountered the gate, pinger, buoy and torpedo tasks in previous years, the team is confident that Matsya 6C can complete them.

The vehicle has been tested extensively in the swimming pool, and various decisions have been made across subdivisions based on testing results. Our core ideology was improving the reliability of existing features and testing extensively before adding new features. To that end, various localization methods were tested, and the most promising method was implemented. Multiple cameras were tested, and the Basler AG was chosen as the front camera for its low latency, higher fps, and bright and vivid feed. In RoboSub 2022, we faced issues procuring the USA-equivalent components for pneumatic actuation, and hence we decided to move to a different type of actuation. Various types of actuators were discussed, and results were compared before we decided to use electromechanical actuators. These are just a few of the many testing and experience-based decisions that we have made this year.

This year, we will deploy only one vehicle, Matsya 6C. We plan on doing the coin flip and getting all the style points we can during the gate task, as the vehicle has been rigorously tested and is capable of high-speed rotations. After going through the appropriate side of the gate based on the chosen destination, the vehicle will bump the corresponding buoy as part of the "Start Dialing" task. Scans will be performed before each task to find and localize the task corresponding to our chosen destination. Next up, the vehicle would place markers into the appropriate bin as part of the "Location" task. Scans would be performed while the vehicle moves in an outward spiral in order to find the proper bin before the servo-based arm performs the task. After these tasks, we would request the random pinger selection and attempt the "Goa'uld attack" task or the "DHD" task based on what the pinger gives. For the "Goa'uld attack", our vehicle will attempt to fire our spring-loaded torpedoes through both openings. And for the "DHD" task, Matsya would attempt to place the chevrons in our chosen bins with object detection using the bottom camera. After completing these tasks successfully, the vehicle would resurface through the octagon.

II. Vehicle Design and Analysis

A. Mechanical Subsystem

The mechanical subsystem ensures the robustness of the design by performing various structural, hydrodynamic, and thermal analyses on the vehicle. The mechanical design can be bifurcated into the hulls and the frame (structure and component positioning). A total of 8 thrusters have been used to provide active control of all 6 degrees of freedom to the vehicle. The vehicle is also equipped with various manipulation systems (Gripper, Torpedo-Launcher, and Marker-Dropper).
Any potential design undergoes an iterative procedure involving prototyping and critical design reviews until all design requirements are met. The following sections present the work on improving the structural integrity of frames and the new manipulator designs.

Frame:

The skeleton-type frame is 5mm thick and is made of alloy Al-6061. Considering the vehicle's instability and buckling that occurred at RoboSub 2022, the frame was strengthened by changing its thickness and shape to account for the new actuation systems, and the legs were made wider to reduce wobbling. In addition, the various beams carrying different sensors and hulls were made thicker to withstand greater loads and more fatigue resilient.

Actuators:

This year we have come up with entirely novel designs for actuation. Three electro-mechanical systems are replacing the previous pneumatic systems for better control and reliability. Instead of linearly actuated pistons, waterproof servo motors will be used along with simple 3-D printed parts.

(a) *Marker-Dropper:* The new Marker-Dropper uses a single servo motor to drop two or more markers independently. It is mounted with 3D-printed parts that are lightweight and simple to assemble. The mechanism consists of a revolver and a stopper. The markers are loaded into the revolver and rotated until they fall through an opening. The 3-D printed markers are bottom-heavy, ensuring a smooth, straight trajectory toward the sea floor.

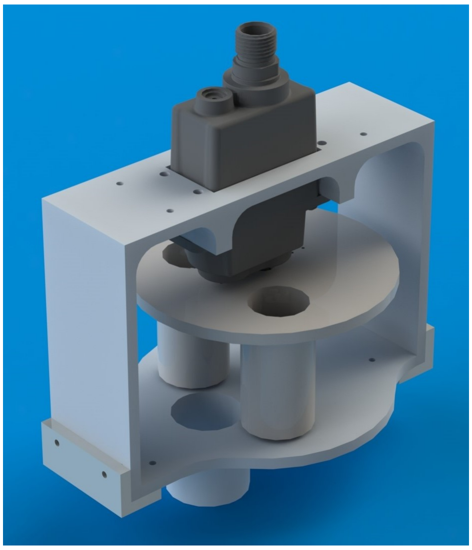

Figure 2: Marker-Dropper

(b) *Torpedo Launcher:* The new torpedo shooting mechanism uses a simple yet elegant way to shoot two torpedoes independently using a single servo motor. The mechanism uses springs to propel the torpedoes, while the servo motor is attached to a stopper. The torpedo is loaded in the back half of the mechanism with a compressed spring attached to the back. The stopper is then rotated to release the torpedo, which gets propelled using the potential energy stored in the compressed spring. The torpedoes are neutrally buoyant to ensure they remain at the same depth throughout their trajectory.

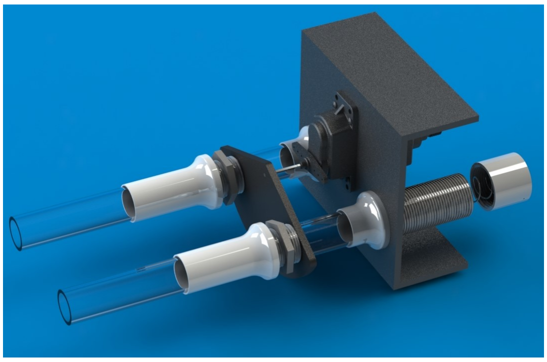

Figure 3: Torpedo Launcher

(c) *Gripper:* The new mechanism utilizes a single servo motor to actuate one of the gripper fingers, which subsequently triggers the movement of the other finger through a gear. These fingers are specifically designed to interlock with each other, ensuring that objects are securely held within their grip. Furthermore, the design allows a diverse range of object shapes and sizes. We employed the stereolithography 3-D printing technique to manufacture the fingers for the precision of gear teeth and a better finish.

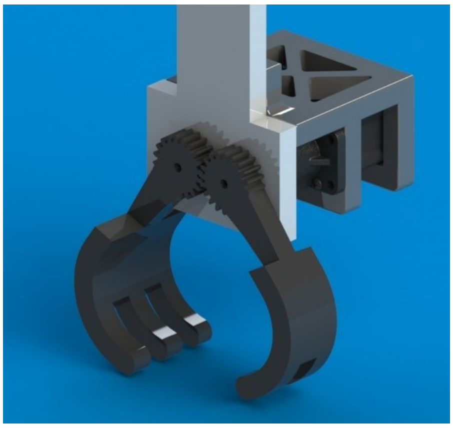

Figure 4: Gripper

B. Software Subsystem

The software subsystem encompasses a comprehensive stack designed to decode Matsya's environment (as captured through its various visual, acoustics, and inertial sensors) and process this information to facilitate finely-tuned autonomous underwater operations.

Our source code is written primarily in Python and is organized into distinct core modules, including vision, acoustics, localization, navigator, controller, and mission control. We employ the Robot Operating System (ROS) to enable effective communication between these modules, which facilitates inter-process communication through messages and services. Each module operates as an independent process, running on dedicated nodes within the system.

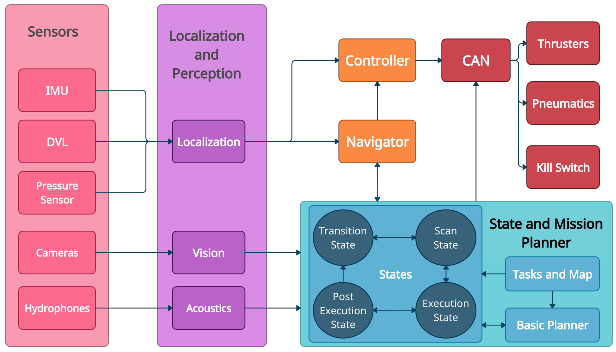

Figure 5: Software architecture of Matsya 6C depicting inter-package communication facilitated by ROS

A Software Reset:

The codebase has undergone a significant reconfiguration and refactoring to embrace a more functional, minimalist, and modular design approach. In this effort, we decided to shift our primary language from C++ to Python, which offers numerous advantages such as improved readability, comprehensibility, and ease of modification. Python also provides extensive library support, particularly in image processing and complex mathematical operations, which make up for any speed loss compared to C++.

The architecture of each module has been crafted to prioritize the segregation of three fundamental functionalities: systematic decoding of data and parameters, high-frequency module communication, and efficient implementation of the core logic. This deliberate separation has facilitated a more functional and streamlined design for the source code. Additionally, we consciously moved away from object-oriented programming (OOP) concepts like inheritance and polymorphism, instead opting for a procedural and interface-based design wherever feasible. This architecture enables us to build upon a more straightforward and intuitive structure, empowering our team to improve and innovate faster.

Enhanced Control Allocation and Power Ratios:

This year we have upgraded our force allocator to a Control Effectiveness Matrix (CEM)[5]-based allocator. This uses a pseudo-inverse of the CEM to determine the thrust force to be given to the thrusters To compensate for the deterioration of thrusters and the physical effectiveness of some thrusters in some PWM settings, we incorporated linear power coefficients for all thrusters in forward and backward directions to get better compensation accuracy.

Action-Based Task Execution:

Our new mission control framework leverages the concept of an "action" as the fundamental unit, an essential operation that the vehicle can perform. Navigation, scanning, actuating, and alignment are standard components utilized across multiple tasks.

Encoding tasks as a series of modular, reusable actions has allowed us to switch the underlying logic for each task through a simple interface, while also enabling the generation and modification of plans for new tasks in a clear and straightforward manner.

Transitioning to Unity simulator:

In our pursuit of improved testing capabilities, we decided to transition from Gazebo to Unity as our vehicle's primary simulator. This change brings several advantages, including simpler environment creation and reduced processing time, facilitating easier training and testing of our vehicle across various use cases.

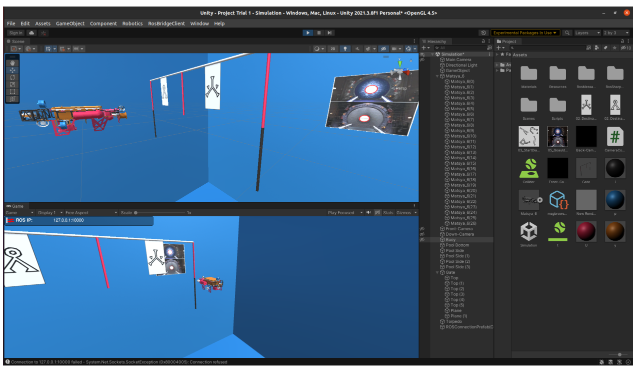

Figure 6: Representation of Unity simulator with tasks

We utilized a ROS connector to integrate the Unity simulator with our codebase. This connector allows us to emulate the driver and camera data feed while simultaneously interfacing with the vehicle's thrusters to accurately simulate the vehicle's powering.

Inference From Detected Geometries:

We have developed a robust method to derive accurate object locations based on detected geometries, leveraging the object's real dimensions, the dimensions of images captured by the camera and corresponding bounding boxes obtained through our YoloV5 model, and the vehicle's current position and orientation. This represents a significant advancement from the previous approach, which relied on rough estimations using the ratio of actual and image areas.

C. Electrical Subsystem

The electrical subdivision of the team connects the software and mechanical subsystems by powering them and interfacing multiple nodes using different communication protocols. The SBC does the higher level processing such as vision, mission planner and controller. It reads/publishes data from various sensors (IMU, DVL and pressure sensor) and the electrical stack on serial and CAN bus, respectively.

The CAN bus connects the Single Board Computer (SBC) and the electrical stack[3], and handles the transfer of control commands and status updates.

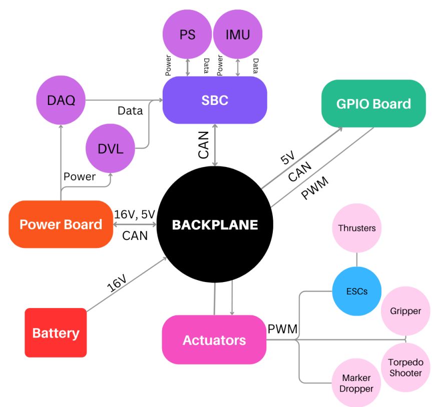

Figure 7: Electrical architecture diagram exhibiting the internal communication and power distribution

Electrical Stack:

The Electrical Stack serves two purposes: power distribution and general-purpose input/output. It consists of 4 PCBs, one power board for power distribution, one for

GPIO, one auxiliary backplane to facilitate easy connections with the onboard computer and peripherals, and one debug board which gathers data during runs.

(a) *Power Board:* One of the key changes on the power board involves the replacement of the PTN78060 DC-DC step-down regulator with the TPS5430DDA series switching voltage regulator for the generation of a 5V line using the battery input of 16V. The implementation of the TPS5430DDA, also significantly shrinks the size of the power board. However, since the electromechanical actuators can potentially draw currents higher than TPS's rated 3A[4], the power supply of the actuators was shifted from the on-board electrical stack to a peripheral buck convertor.

(b) *GPIO Board:*
The pneumatics lines were repurposed as Pulse Width Modulation (PWM) lines for the electromechanical actuators, which shrank the size of the GPIO board significantly. Moreover, redundancy has been integrated into the PWM lines, ensuring the availability of alternative signal paths in the event of a component failure.

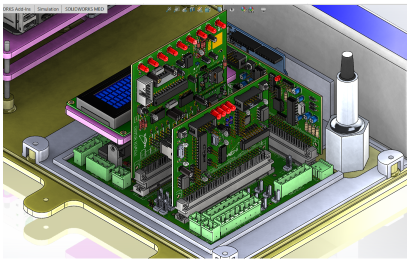

Figure 8: The Electrical Stack in Matsya 6C

Electromechanical Actuation:

Pneumatics were replaced by electromechanical systems for all actuators aboard the vehicle: marker-dropper, torpedoes and gripper. Each electromechanical actuator consists of a waterproof servo motor (SER-110X by BlueTrailEngineering[2]) with custom apparatus.

Cameras:

For vision, the vehicle was readied with a Basler for the front camera and a GoPro for the bottom camera.

The Basler ace acA1920-40gc Color GigE Camera is a specialized camera designed for underwater imaging[1]. With a resolution of 1920 x 1200 pixels, it can capture detailed images with excellent clarity and great color capability. The GigE (Gigabit Ethernet) interface allows for fast and reliable data transfer. Additionally, the Basler camera offers adjustable exposure settings, autofocus capabilities, and image stabilization, which further enhances its performance in underwater imaging. These features allow for better control over image quality.

The GoPro Hero 11 Mini is more compact in size which enables us to easily mount the camera in a tighter space. In addition to its size, the GoPro Hero 11 Mini boasts improved FPS capabilities, wide-angle features that excel in capturing photos and videos in dim light, and its plug-and-play functionality, consisting entirely of a single USB-C cable which conveniently handles power supply and data transmission.

III. Experimental results

From a mechanical perspective, the vehicle's waterproofing was validated by keeping it overnight in the swimming pool at a depth of 2.5 meters for more than 12 hours. Floats were added to the vehicle's frame to enhance the vehicle's stability and achieve a favorable center of buoyancy and center of gravity alignment.

We observed 15% drift in position calculated using the DVL solely. By instead integrating the velocity provided by our DVL, using the IMU's orientation readings for the transformation, we were able to localize the decrease the drift to 0.5%-2%, allowing us to localize the vehicle more robustly.

Using the CEM-based allocator, we have been able to achieve effective open-loop control in all 6 degrees of freedom after tuning the associated parameters extensively. This addressed many previously faced problems, such as thrust imbalances and residual torque. The current controller employs the well-known PID control law in all 6 degrees of freedom. Post tuning, the vehicle has been able to reach setpoints of up to 20 meters.

Through extensive controller testing,

we observed that certain navigation plans were more suited to longer distances, while simultaneous control of all degrees of freedom offered efficient solutions for smaller position adjustments. To optimize navigation performance, we have implemented a distance-dependent navigator. This navigator systematically executes a depth-first plan when operating with farther away setpoints. This approach ensures efficient traversal in larger-scale movements. Conversely, the navigator activates all degrees of freedom simultaneously for shorter displacements, enabling precise control to achieve accurate positioning.

The new computer vision stack uses the YoloV5s object detection model and an in-house, optimized camera driver for the Basler AG. It delivers a peak performance of 45 FPS. The stack's effectiveness was tested by training the YoloV5s model using a dataset containing images of props taken in our swimming pool. The stack is able to detect props with a confidence of 70% to 95% depending on the prop, and it is able to localize them accurately within 10 cm of error.

Task-specific testing:

- Gate task: With the two images that have been added to the gate, detecting the gate has become much simpler. We are 100% confident that the vehicle will complete this task in style.
- Buoy task: Detecting the buoy has become a more complicated affair due to the randomly distributed symbols. However, by labeling each symbol as a separate entity, the vehicle has been able to detect the buoy. Having also worked with prismatic buoys in previous years, the team is 90% confident in executing the buoy task this year, which involves a planar buoy.
- Bin task: Due to the highly characteristic colors of the bin and the lid, we expect high accuracy from our vision stack. The probability of success with an open bin is estimated at 90%. Equipped with a servo-operated gripper, we are 75% confident of executing the closed bin task.
- Torpedo task: Extensive testing and improvement of localization have helped us to make the vehicle accurate and stable. Along with the bright red border, which the vehicle has been able to detect with a confidence of above 80%, we are 70% confident about completing this task.
- Pinger task: The vehicle's acoustics module has been tested extensively, and it has very high accuracy with respect to the estimation of the direction of arrival. We are 95% confident that we can go towards the desired pinger.
- Octagon task: The newly introduced randomness poses a challenge to our vision stack when it comes to identifying the octagon. However, labeling each symbol as a separate entity has shown great results, and we are 85% confident of detecting it. The chance of picking up a bottle is estimated to be around 50% with our new servo-operated gripper.

IV. Conclusion

Mastya 6C has been tested extensively for the three months approaching RoboSub, often redundantly in the face of unforeseen failures and an ever-present time constraint which only got tighter and tighter. However, the extensive testing performed has refined its systems to such an extent that most results are now reproducible. Being the most advanced vehicle the team has made so far, it can easily adapt to new features and adopt them without requiring major developmental adjustments, and serves as an excellent platform for the team to further extend its research in underwater and autonomous robotics.

V. Acknowledgements

The team would like to thank the Industrial Research and Consultancy Centre of IIT Bombay for administrative and monetary support during the project and for helping us participate in RoboSub 2023. The support of the Dean R&D's office was crucial in the successful execution of the project.

References

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Appendix: Component Specifications

Component	Vendor	Model/Type	Specs	Custom/ Purchased	Cost USD	Year of Purchase
Buoyancy Control	Designed In-House	Dead Weights & Foam	-	Custom	-	-
Frame	Designed In-House	Aluminium & Delrin	4 kg	Custom	800	2022
ASV Hull Form/ Platform	Designed In-House	Aluminium Hulls w/ Acrylic Endcap	8 Hulls weighing 22 kg Depth Rating : 70 ft	Custom	1800	2022
Waterproof Connectors	Designed In-House	Aluminium	24 connectors weighing 1.5 kg in total	Custom	150	2022
Propulsion	Blue Robotics	T200	11 and 9.5 kgf forward and backwards	Purchased	1600	2022
Motor Control	Blue Robotics	Basic R3 Version	30A PWM controlled brushless motor speed controller	Purchased	200	2022
High Level Control	Microchip Technology	Atmega 328P and 32M	Low Power CMOS 8-bit RISC Microcontroller	Purchased	15	2022
Actuators	BlueTrail Engineering	SER-110X	29.0 Kgf-cm of torque, 140 degrees range	Purchased	340	2023
Battery	SkyCell	LiPo Battery	4 Cell and 16000mAh x 2	Purchased	400	2022
Converter	Texas Instruments	TPS5430DDA	Wide Input Range, Step-Down Converter	Purchased	4	2022

FPGA	Xilinx	Zybo Z7-20	Programmable logic equivalent to Artix-7 FGPA, DDR3L memory controller with 8 DMA channels and 4 High Performance AXI3 Slave ports, 667 MHz dual-core Cortex-A9 processor	-	300	-
Regulator	Mini-Box	M4ATX	High efficiency 250W output, $< 1.25mA$ standby current	Purchased	80	2022
CPU	AMD	Ryzen 3400G (4C8T)	4 Cores (4.2GHz), 8GB RAM	Purchased	-	2022
GPU	Nvidia	GeForce GTX 1660ti	GDDR5, 6GB, 120W	Purchased	300	2022
Internal Comm Network	Microchip Technology, CAN USB	MCP 2515, MCP 2551, CAN USB	1 MB's operation limit	Purchased	150	-
External Comm Interface	-	Ethernet	10-100 Mb/s	Purchased	-	-
Inertial Measurement Unit (IMU)	Microstrain	GX5	-	Purchased	-	2022
Doppler Velocity Log (DVL)	Waterlinked	A50	-	Purchased	-	2022
Camera(s)	GoPro	Hero-11 Mini	-	Purchased	-	2023
Camera(s)	Basler	Ace acA1920-40gc Color GigE	-	Purchased	-	2023
Hydrophones	Teledyne	RESON Underwater TC 4013	-	Purchased	-	2022
Algorithms: Vision	YOLO v5	-	Parallel and Sequential processing, lens formula	-	-	-

Algorithms: Acoustics	FFTW	Time difference of arrival	Filtering in frequency & time domain	-	-	-
Algorithms: Localization and Mapping	Orocos BFL	Extended Kalman Filter	EKF applied on position found by integration of DVL velocity	-	-	-
Algorithms: Autonomy	-	State Machine & Mission Planner	Probabilistic (or Finite) state machine for mission planner, designed in-house	-	-	-
Open Source Software	OpenCV, Eigen, ROS, YOLO v5	-	-	-	-	-