ROBOFERT: Human - Robot Advanced Interface for Robotic Fertilization Process.★

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Abstract. The interfaces for Human-Robot interaction in different fields such as precision agriculture (PA) have made it possible to improve production processes, applying specialized treatments that require a high degree of precision at the plant level. The current fertilization processes are generalized for vast cultivation areas without considering each plant's specific needs, generating collateral effects on the environment. The Sureveg Core Organic COfound ERA-Net project seeks to evaluate the benefits of growing vegetables in rows through the support of robotic systems. A robotic platform equipped with sensory, actuation, and communication systems and a robotic arm have been implemented to develop this proof of concept. The proposed method focuses on the development of a human-machine interface (IHM) that allows the integration of information coming from different systems from the robotized platform on the field and suggest to an operator (in a remote station) take a fertilization action based on specific vegetative needs to improve vegetable production. The proposed interface was implemented using Robot Operating System (ROS) and allows: visualizing the states of the robot within the crop by using a highly realistic environment developed in Unity3D and shows specific information of the plants' vegetative data fertilization needs and suggests the user take action. The tests to validate the method have been carried out in the fields of the ETSIAAB-UPM. According to the multi-spectral data taken after (2 weeks after being planted) and before (3 months after growth), main results have shown that NDVI indexes mean values in the row crop vegetables have normal levels around 0.4 concerning initial NDVI values, and its growth was homogeneous, validating the influence of ROBOFERT.

Keywords: Virtual reality · ROS · Robotics · Precision agriculture · Human Machine Interface · Image Processing ·

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1 INTRODUCTION

Recent developments in specialized software with better communication managers and graphics engines, combined with the low-cost robotic systems increase, have made it possible to implement more robust integrated systems to execute specialized robotic applications. The remote execution, monitoring, and control of these processes have been possible through the implementation of IHM, allowing an operator to supervise and control a process from a remote station.

One of the approaches in recent years of this type of robotic application focuses on precision agriculture. The Sureveg project (”Strip-cropping and recycling of waste for biodiverse and resoURce-Efficient intensive VEGetable production”) aims to develop robotic systems and intelligent machines to intensify organic vegetable crops in rows (6). Within the field of PA, several projects have been carried out involving robotic systems for the execution of tasks (18; 22), mainly: fertilization and irrigation (7), location of plants and fruits (13), mapping(20), through the use of sensory systems such as: RGB, Multispectral cameras(21), Laser (24).

The recurrent monitoring of robotic applications in AP is developed through conventional interfaces that focus on the transmission of RGB videos captured from one or more external cameras or on-board the robot, which show to the user, the status of the crops or the robot (1), some perform first processing of the images generating segmentation of areas of interest (3). However, the biggest deficit found after review the state-of-the art lies in the lack of information shown to the operator during the online process for subsequent execution of actions.

The main contribution of this work is to improve the intensive production of vegetables grown in rows through the implementation of a robust method for remote monitoring of vegetative variables, crop status, the status of the robotic platform, through visual information captured from on-board sensors of the robotic platform. These data are displayed in a highly realistic representation of the crop field, managed by an IHM. The system, in addition provides an initial suggestion to apply or not the treatment in the current plant and allows to remotely activate the organic fertilization by means of the robot in the field, by managing different buttons.

In this paper, the interface consists of a virtual environment modeled from the real system (RV), previously captured by a 3D system, it consists of a group of cultivation rows of 20 meters long, for various types of vegetables such as cabbage and beans. The simulated environment has the count of the number of fertilized plants the activation and deactivation of the robotic arm, application of the fertilizer to each plant and location of the fertilized plants, this process works in conjunction with the physical robot and the monitoring of the process is seen through the robot’s camera.

Through the proposed method, ”ROBOFERT” seeks to improve the growth of vegetables grown in rows. The main results, after carrying out tests in the fields of ETSIAAB-UPM (with row plantations of cabbage), have shown an improvement in the growth of vegetables cultivated in rows. This hypothesis has been corroborated using NDVI index captured from multispectral images of the cultivation before (initial phase of plant growth) and after fertilization (after three months of vegetable growth).

This paper is structured in five sections. Section 2 describes the most relevant works in the state of the art, Section 3 shows materials and methods in detail. Section 4, containing the experiments and results. Finally Section 5 presents the main findings.

2 RELATED WORK

The proposed method has taken as a reference the most relevant works within the field of application of interfaces in robotic agriculture, analyzing the strengths and weaknesses of the same to develop a robust and functional system, then the main topics involved in the proposed development are discussed.

2.1 Interfaces in robotics applied to agriculture

The immersive interface propose focuses on introducing the operator to the mission scenario; through a rich and detailed reproduction of it, there are three fundamental types of immersive technologies: virtual reality (VR), augmented reality (AR), and mixed reality (RM).(29; 23)

RA superimposes images or virtual elements within a video of the real environment; the related projects in AP are: identification of insects for pesticide application (19), control and monitoring of agricultural tractors (26), Mapping with UAV (11). RV shows digitally synthesized scenarios with interactive elements; the scenarios scanned in 3D for fertilization training, pest location, and plantation monitoring, (16; 24), is also applied for greenhouses (5).

Among the different robotics projects in the AP, NARCH (National Agricultural Research Center for Hokkaido Region) is one of the most relevants, which has an adaptive interface in a virtual and physical way for its maneuverability. This project is based on the tele-operation and maneuverability of an agricultural tractor (18).

Another one is SAVSAR (Semi-Autonomous Vineyard Spraying Agricultural Robot), the adaptive interface consists of robot battery level, control of robot movements and camera movement, front and rear camera screen presentation of the robot, and additional information from sensors (visual and auditory), the robot performs inspection and distribution of fertilizer on a vineyard (15).

ROBOTIC WEED CUT is remotely operated through an adaptive interface, which consists of two prototypes, first: with screen navigation buttons, emergency stop, geographic orientation, and external camera visualization, second similar to the first with the difference of the robot's maneuverability controls, battery level, target count and the visualization of the fruit to be sprayed (17; 12).

RHEA a project of collaborative robots between terrestrial and aerial robots, which operate telematically and autonomously; the aerial robot flies over the work area and locates the plants and weeds to be sprayed; the virtual interface consists of a virtual environment, modeled to starting from the real system, previously captured by a 3D system. The spraying of crops autonomously traced the appropriate path from the data collection of the aerial robot; the tele-operated control is developed in the virtual environment (27).

The Figure 1 shows the increase of articles related to Interfaces for Agricultural Robotics; in the web of knowledge, shows an increase of around 22 % of articles per year. Which allows to corroborate the importance and rise of this type of interfaces

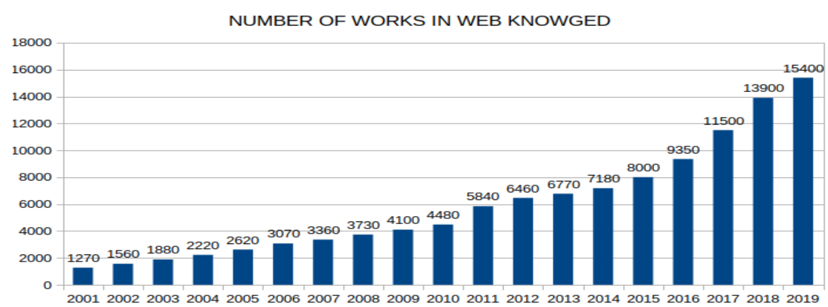


Fig. 1. Numbers of works in the Web of Knowledge including Interfaces for Robotic Agriculture as topic.

In table 1 a comparison is shown between the advantages of the main methods developed and the proposed method. The proposed interface shows a great advantage and contribution to the main related works or similar methods in this field, the metrics of components proposed are: A:RGB Images, B:Multispectral Images, C: Security Systems, D: Assisted Fertilization, E: Real Time Model Visualisation in inmersive interface..

Table 1. Comparative of the proposed method with current developments.

Projects	A	B	C	D	E
NARCH (18)	x		x		
SAVSAR (1)	x			x	
SEARFS (10)		x	x		
VINEYARD (2)	x			x	
ROBOTIC ARM (12)	x	x		x	
ROBOT WEED CONTROL (28)	x	x		x	
ROBOTIC WEED CUT (17)	x	x		x	
TERRAIN MAPS (24)	x				
TRACTOR RA (26)	x		x	x	x
RHEA (27)	x		x	x	x
ROBOFERT	x	x	x	x	x

The proposed system to integrate all subsystems and manage the communications between field robot and interface is ROS, because of this nodes, topics and multi-platform structure (2). Some others related works uses Matlab (10; 28) or serial protocol (9; 25).

3 MATERIALS AND METHODS

For this research, a robotic platform has been implemented (Figure 2) that will carry out fertilization in the field. It consist of an aluminum structure with wheels, coupled with an Igus CPR5DOF Robot by means of a custom-designed plate for the base. The platform is instrumented with an RGB camera, a PARROT-SEQUOIA multispectral camera, 3 laser lidar sensors and an actuation systems (a nozzle and pumping system to spray the liquid) in the prototype. The figure 2 shows the robotics platform described on the crop row.

For the validation of the proposed method, fertilization tests have been developed using the robotic platform in the crop fields of ETSIAAB-UPM located at ETSIAAB-UPM (40°26’38.9” N 3°44’19.3” W) in Madrid. Which contains rows of crops with cabbages in the initial growth phase, a stage in which the application of fertilizer is convenient.

(a) Robot CPRIgus 5DOF used. (b) Robotic mobile structure on ETSIAAB-UPM fields.

Fig. 2. Robotic mobile platform description.

The proposed method focuses on develop a continuous and robust interaction between the monitoring of the vegetative variables of the crop, the state of the robot in the field, and the decision-making by the user, for the execution of tasks of organic fertilization at the individual plant level on row crops, seeking an efficient intensive production of cultivated vegetables.

3.1 Interface for monitoring and control

The interface implemented is shown in the figure 3a-b;it has been developed in Unity3D, which has been used since it meets the requirements to implement the proposed method: it has a powerful graphic engine, allows wireless communication with ROS through Ros-Bridge (to manage the sending and receiving of data, through topics). The Unity Interface laptop features a Core Intel I7-10th Gen processor and Nvidia GEFORCE-GTX 1660-Ti graphics card to support data flow management and visuals.

(a) Representation of a plant on the crop that doesn't require fertilization.

(b) Representation of a plant on the crop that requires fertilization.

Fig. 3. Advanced interface for monitoring and control the fertilization process .

The interface is made up of an environment that recreates the crop field's details, mainly: crop rows, vegetables, trees, agricultural machinery, plants, etc. In order to represent the states of the platform at each moment.

On the left side in blue squares of figures 3a-b, the information concerning the current plant (fertilization suggestion and nozzle status), the on-board camera's image, and the platform control buttons are shown on the environment. On the right side, the multi-spectral information concerning the row of the real crop is shown, and in the upper part of the IHM, the suggestion of the system corresponding to the platform's displacement is shown.

The data received in the interface mainly show the variables of vegetative interest of the crop and robot in the field. In other way, the data sent by the interface, manages the start of the planning and execution processes of the fertilization process with the robotic arm.

The data shown in the interface, coming from the sensors read from ROS are:

- Background Field: Representation of the robot model in the field.
- Fertilization Status: Current status of the nozzle.
- Plant Number: Number of plant processed in the row.
- Plant Status: Suggestion issued by the system to apply or not the treatment.
- System Output (S-O): System suggestion for platform advance.
- In the crop row's multispectral image (left side), the red circle shows those that require fertilization. The green circle suggests that they do not require treatment.
- RGB image transmitted of the current process by the on-board camera.

On the other hand, the operator's actions can carry out based on the information provided, and the system's suggestion through the bottoms:

- Turn on all the systems.
- Yellow button: Start planning robot movements to apply the treatment around the current plant and start the movement. This is developed in the on-board computer of the robot using Moveit planner tool, based on the row PC. This fertilization strategy method was implemented using the CCD method to solve the inverse kinematics based on the vegetable characterization this process is described at detail in (7).
- Back button: Process stopped.

3.2 Structure of sub-systems connection

The figure 4 shows the subsystems' main interaction scheme for the bidirectional data flow, between the interface and the robotic platform on the field. The structure has five subsystems that develop specific functions in the fertilization process. Four of these correspond to the platform, and the remaining subsystem corresponds to the interface (with wireless communication). These subsystems are:

- Point Cloud Data Processing: Field reconstruction through point clouds (PC), using the laser system, described in (8; 14).

- Trajectory Planner: Collision-free trajectory planning based on PC.
- Fertilization: Nozzle drive.
- Real Robot CPR: Execution of movements of the robotic arm.
- User Interface: IHM for monitoring and control (remotely).

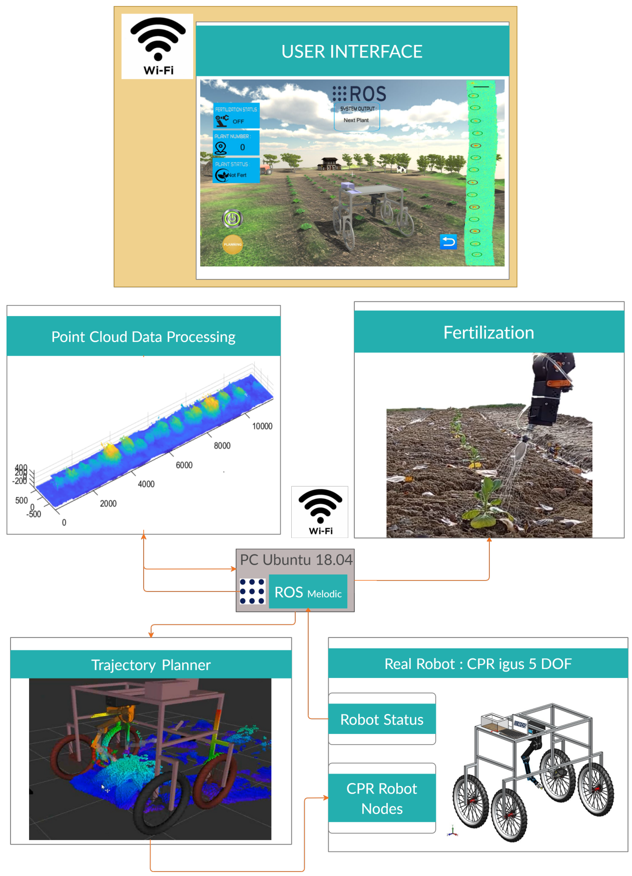


Fig. 4. Schemes of interconnections between subsystems for the fertilization process (Uner Interface is remote, the rest of the subsystems are in the field).

The execution of processes and data flow is carried out on two computers; the first is on board the platform (Ubuntu Operating System) and is execute tasks for reading the sensors and controlling the robot's actions; The second computer (Windows Operating System) is in the remote station, it contains the interface developed in Unity. Computers communicate using TCP / IP protocol through a Wi-Fi network.

ROS manages the information flow; the different data is published through specific topics (/Sensor.CompressedImage for images, /Geometry.Pose for the platform's position, /Sensor.Joy for the state of the robot joints) via Ros-Bridge to the interface.

4 EXPERIMENTS AND RESULTS

The experiments development was carried out in a row of transplanted cabbage crops. Previous analysis has been made on these plants (in a first continuous pass) to evaluate their vegetative needs and determine which needs fertilization.

For the development of the experiments, the platform will move from the beginning to the end of the row (already with the data analyzed). In the interface, the system that controls the output data of the interface will previously load the vegetative information of the row to issue the suggestions to the operator.

The results of the field execution and interface operation are shown in the appendix A.

4.1 Field tests

To start the process, the interface through the System Output (S-O) suggest the user to place the platform on the first plant; once the platform is placed, its data and suggestions of apply or no the fertilization is displayed while it lasts. The O-S process set a massage of "Wait to Finish"; once the task is completed, new O-S massage will be "Next Plant" to indicate the platform's advance.

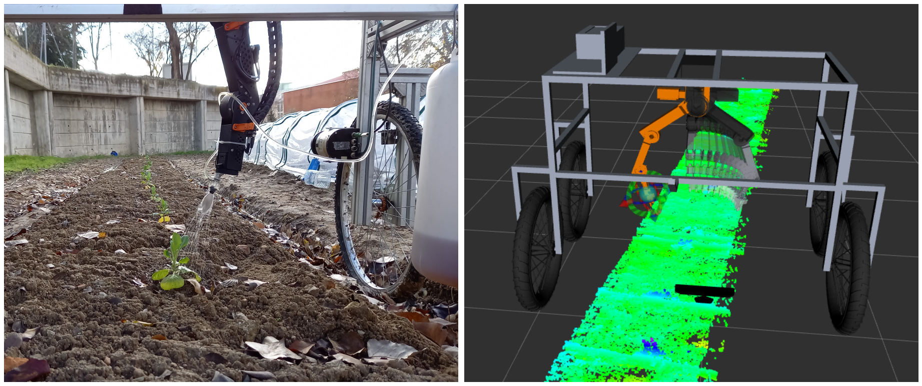
These data, together with the visualization of the robot through the image transmitted by the on-board camera, will allow the user to press or not the buttons that start the planning and execution of robot arm movements. Figures 3a-b, show two cases where the treatment should and should not be applied.

The first case in the figure 3a, corresponds to a plant on which the treatment must be applied, the data for plant number (6), plant status (Apply Fert), fertilization status (Applying) are shown, in the same way, the System Output tells the user to wait for the process to finish.

The second case in the figure 3b, corresponds to a plant that does not require treatment, the data shown are plant number (7), plant status (Not Fert), fertilization status (OFF), in the same way, the System Output indicates to the user, you must advance to the next floor.

4.2 Execution of fertilization through trajectory planning

Figure 5a, shows the data captured by the sensory system from RVIZ (ROS's own information display), shows the platform with the robotic arm suspended in the center, the current position is represented in orange, while the path that the arm will travel to apply the fertilizer it is described superimposed in gray, like a semicircle around the base of the plant.



(a) Interface showing data of a plant that doesn‘t need fertilization and current robot status.

(b) Interface showing data of a plant that needs fertilization and current robot status.

Fig. 5. Interface showing different cases of plants in the row crop.

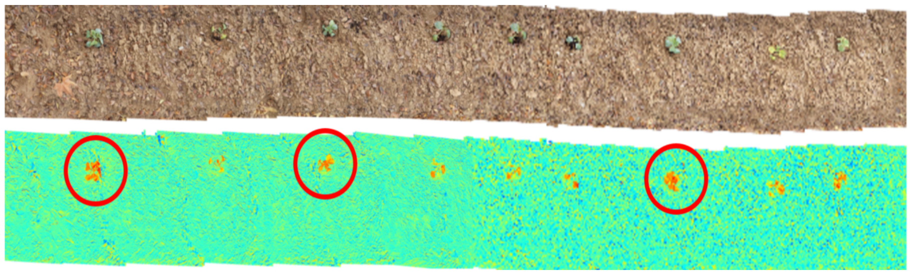
The PC data concerning the 3D reconstruction of the current row (figure 5b) is represented in green-blue (as a false depth color, if it is bluer, it is higher) and allow the robot to locate itself within the environment and plan the trajectories in the function of the relative position arm/plant.

The figure 5a, shows the tool placed in the end of the robotic arm, with an angle of inclination that place towards the plant's base to describe a semicircular trajectory. The nozzle has been activated by the system, based on the arm's current position (close to the base and with an optimal angle of insertion to SPRAY the liquid organic fertilizer on the base), it remains activated until the semicircular path is finished.

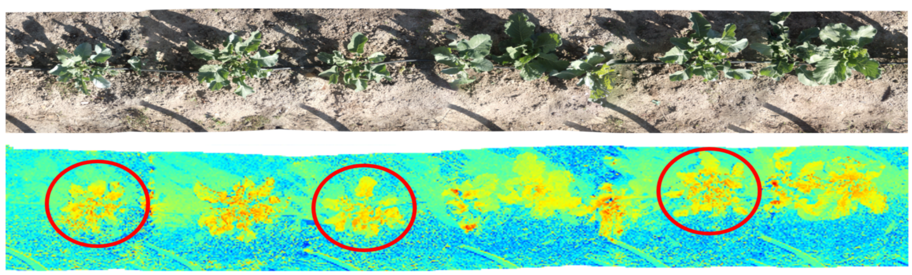
4.3 Comparison of multi-spectral images for testing the influence of the method proposed.

To verify the influence of the proposed method on the incidence on the growth of the planted vegetables and regulation of NDVI indexes, we have compare the initial growth stage and the NDVI indexes of a section of the crop row and the same vegetables produced after three months. The figure 6a shows the mosaic of the RGB (upper) and multi-spectral (lower) images for the transplanted vegetables in the initial stage, with a mean diameter of 10 [cm]. The circles in red show those vegetables that require fertilization. This analysis has been carried out based on the NDVI (Normalized Difference Vegetation Index) indices that evaluate the quality and development of vegetables. This part of the work was detailed in (4).

The figure 6b shows the vegetables after three months of growth; after applying the method proposed in the cultivation, the mosaics for the RGB (upper) and multispectral (lower) images show an optimal development of the



(a) Crop images before fertilization



(b) Post-fertilization crop images

Fig. 6. RGB and multi-spectral analysis of the influence of the proposed method on the growth of vegetables. Plants are numerated form left to right [1-9] as reference.

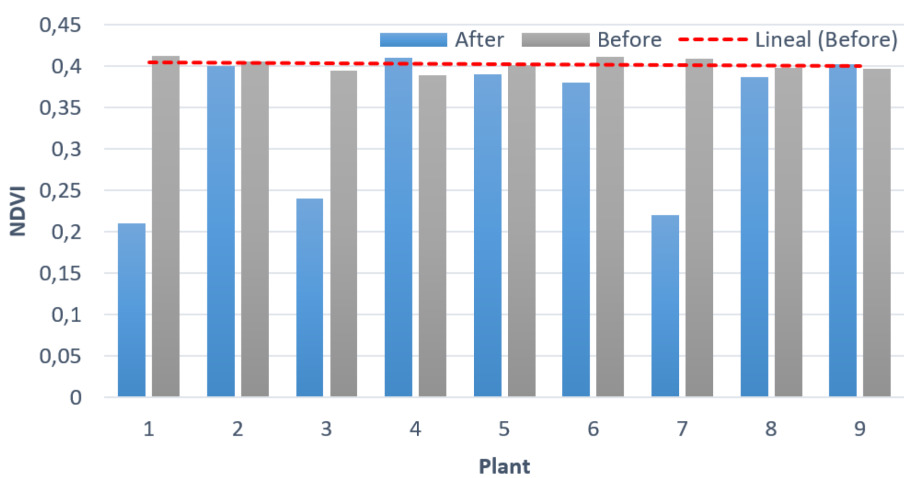


Fig. 7. Comparison of the NDVI mean value calculated after (blue) and before (gray) plant growth.

vegetables allowed verification the proposed method. The same vegetables in the figure 6a, have been marked in red to show the change produced concerning those initially transplanted. The result is a crop that has developed consistent and uniform growth.

Finally, the figure7 shows the before and after variation of the NDVI indices, where it can be clearly seen that in the before (Figure (**?**)a), the three plants marked with a circle have an NDVI index lower than 0.3, which means that their vegetative conditions are not optimal. Later (**?**)b), after applying the proposed method and after its growth, this index improves considerably, and all plants have an average NVDI of 0.4.

5 CONCLUSIONS

We have presented ROBOFERT, a method that proposes, through an advanced interface, improve the production of vegetables grown in rows through organic fertilization executed at the plant level.

The proposed method focuses on monitoring the variables of vegetative interest in a cultivation row and control of a mobile platform equipped with a robotic arm, sensory and actuation equipment to develop fertilization tasks. Through an IHM, the information from the sensory systems is displayed and processed, and transmitted by ROS to an operator located in an external monitoring station, which can or not, execute the fertilization process based on the information and suggestion issued by the IHM.

To validate this proof of concept, tests with the robotic platform and the IHM have been carried out in fields with row crops of cabbage. The influence of using the proposed method has been verified through the analysis of NDVI indices of multispectral sensors, based on images captured before and after cultivation.

The incidence of the use of virtual reality interfaces and robotic tools in the PA has shown promising results. NDVI indexes allows to validate this method. In the initial phase of transplantation, the NDVI index in 3 of the plants in the section of the crop row was less than optimal (0.3), however after applying the method and after their growth, they showed optimal development, which was verified with the average of the NDVI mean index of 0.4.

Regarding future work, the autonomous management of the energetic system of the platform is contemplated through the implementation of an independent source of electricity, solar energy, and battery storage is one of the best options proposed since one of the limitations for mobilization of the platform is currently the dependence on a 220 V source to power the robotic arm, which until now has been supplied by current extension cables.

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