Biologically Inspired Optimization Methods for Image Registration in Visual Servoing of a Mobile Robot

Lazar Đokić, Aleksandar Jokić, Milica Petrović and Zoran Miljković

Abstract—**Image registration (IR) represents image processing technique that is suitable for use in Visual Servoing (VS). This paper proposes the use of Biologically Inspired Optimization (BIO) methods for IR in VS of nonholonomic mobile robot. The comparison study of three different BIO methods is conducted, namely Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimizer (GWO). The aforementioned optimization algorithms utilized for IR are tested on 24 images of manufacturing entities acquired by mobile robot stereo vision system. The considered algorithms are implemented in the MATLAB environment. The experimental results suggest satisfactory geometrical alignment after IR, whilst GA and PSO outperform GWO.**

Index Terms—**Image Registration, Nonholonomic Mobile Robot Visual Servoing, Biologically Inspired Optimization**

I. Introduction

A vision-based control, also known as Visual Servoing (VS), is referred to the use of computer vision data for motion control of intelligent robotic systems [1]. An intelligent Mobile Robot (MR), equipped with two cameras, by its own movement induces camera motion. Therefore, a MR can directly control its movement based on the information obtained from images acquired by cameras. VS involves continuous measurement of the visually observed error between target and current image. MR utilizes computer vision to create a feedback signal and produce the required movement until the aforementioned error reaches zero or defined error threshold. Continuous measurement and feedback control provide great robustness to errors in the system [2]. As is clear, VS heavily relies on image processing for the extraction of useful information such as geometric feature extraction (points, lines, edges, etc.), object classification, pattern recognition, etc. In order to mitigate computationally demanding and time-consuming methods for feature extraction, direct methods that exploit pixel intensities can be used [3]. VS approaches that do not require metric information of the object, its shape, or camera motion produce more versatility and robustness to the error. Direct VS implies the use of pure image signal to design the vision-based control law and the function of Image Registration (IR) is to recover unknown parameters directly from measurable image quantities at each pixel in the image [4]. Accordingly, intensity-based IR can be used to construct control error from the projective parameters that geometrically relate the current image with the target one [5]. In both VS and IR, one of the images is referred to as target (fixed) image, and the other one is the current (moving) image. This similarity allows for the straightforward implementation of IR techniques in VS as proposed in [3] and [5]. In the previously mentioned papers, VS that utilizes IR for image processing is referred to as direct VS. IR, in general, represents the process of geometrical alignment of two images (the target and current image) and can represent a key step in image preparation for the seamless execution of VS. Several different techniques of IR are proposed in the literature, and we address papers where Biologically Inspired Optimization (BIO) methods are used. IR is most commonly used for medical imagery, and it comes as no surprise that BIO is mostly used in medical IR for combining computer tomography and nuclear magnetic resonance data [6]. The authors of [7] have done a comprehensive review of Particle Swarm Optimization (PSO) algorithm in multimodal medical IR and some of the successful applications are presented in [8] and [9]. They concluded that intensity-based IR usually requires the optimization of some similarity metric, and global optimization methods, such as PSO, represent very efficient and effective methods that achieve encouraging results in medical IR. Besides PSO, Genetic Algorithm (GA) still finds application in a number of problems. The authors of [10] employed GA optimization for choosing the optimal values of IR parameters. Similarly, the paper [11] proposed multimodal intensity-based IR based on real-coded GA. The

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aforementioned BIO methods showed improved convergence speed compared to the traditional IR methods, with a more relevant exploration of the search solution space and better alignment accuracy. Recently, the Grey Wolf Optimization (GWO) has emerged as one of the best-performed metaheuristic BIO algorithms for the vast amount of engineering applications [12].

Therefore, in this work, the authors analyze the three above mentioned BIO algorithms for IR application. Moreover, another major difference compared to the previously mentioned VS approaches is the implementation of BIO methods for intensity-based IR in VS. Similar to direct VS, whole images obtained at different viewpoints during the motion of intelligent MR are analyzed. Images are acquired by using two camera sensors (acA1920-25uc - Basler ace area scan cameras). Utilized images are obtained by the stereo vision system of nonholonomic MR RAICO (Robot with Artificial Intelligence based COgnition) in the laboratory model of the manufacturing environment (Fig. 1).

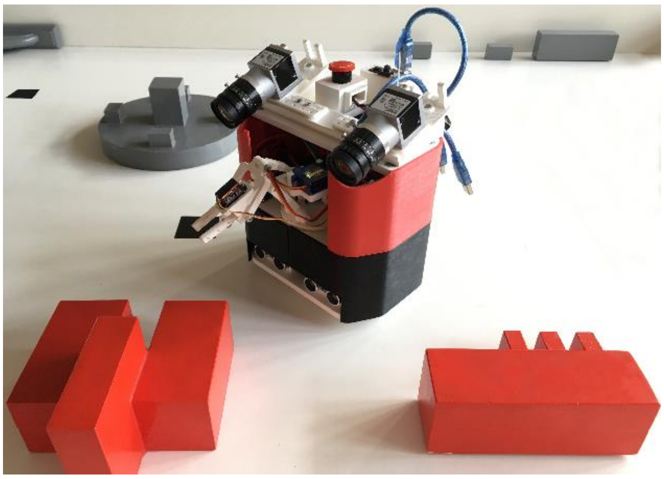


Fig. 1. Nonholonomic mobile robot RAICO

The paper structure is as follows. In Section II problem of intensity-based IR is formulated. Section III contains a brief description of different BIO algorithms while in Section IV Fitness Function (FF) is defined. Comparison of BIO algorithms for intensity-based IR is presented in Section V and Section VI gives concluding remarks.

II. INTENSITY-BASED IMAGE REGISTRATION

The function of intensity-based IR in VS is to geometrically relate two images taken from various MR poses (i.e. position and orientation). Target images are obtained by positioning MR in the desired pose, and current images are taken at different camera viewpoints. In order to successfully carry out intensity-based IR, the current image must contain the same manufacturing entity that is on the target image. Prior to intensity-based IR, acquired images are preprocessed, and afterward, two binary images of manufacturing entities are geometrically aligned. Fig. 2 show the target images of manufacturing entities before and after preprocessing.

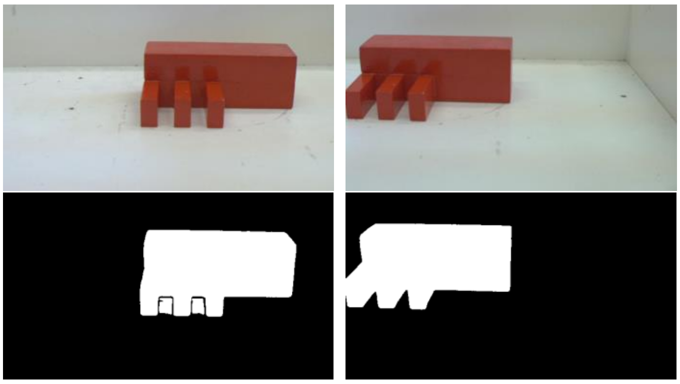


Fig. 2. The target images before and after preprocessing

It must be noted that target images are binarized before motion initialization of MR and binarization of current images is done while moving. Although the preprocessing is not computationally demanding, in combination with BIO real-time implementation is still not possible. A similar vision-based control strategy as proposed in [13] can be implemented for motion control, where the appropriate moving sequence depends on the ratio of translational velocities. The goal of intensity-based IR is to determine a spatial Transformation Matrix (TM) that matches two images:

$$T = \begin{bmatrix} s_X \cdot \cos(\theta) & -s_X \cdot \sin(\theta) & t_X \\ s_Y \cdot \sin(\theta) & s_Y \cdot \cos(\theta) & t_Y \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where s_X and s_Y are scaling parameters with respect to x and y axis, θ is angle of image rotation, and t_X and t_Y represent translation along x and y axis, respectively.

Dimension of TM is 3x3 and via BIO, optimal values of TM elements for geometrical alignment of two rigid bodies (manufacturing entities) are acquired.

III. BIOLOGICALLY INSPIRED OPTIMIZATION METHODS

Many optimization problems can be solved using biologically inspired stochastic optimization algorithms. BIO methods present computationally efficient alternatives to deterministic methods. These BIO methods are population-based approaches that start from a randomly initialized population of solutions and iteratively improve them during the optimization process. Individual solutions with the best fitness function values are kept thorough iterations and new individuals are generated until the maximum number of iterations is reached. At the end of all iterations, the best solution is considered an optimal one. This represents the main disadvantage of BIO methods because there is no guarantee that the found solution is actually the optimal one [14]. There are also some cases where BIO algorithm can be stopped due to the convergence to the local extremum before all iterations are done, defined with early stopping criterium. BIO methods have clear advantages compared to traditional deterministic optimization methods in solution exploration and their wide application in solving various problems is considerable.

A brief description of the analyzed BIO methods for IR in VS are given below.

A. Genetic Algorithm

GA belongs to the class of evolutionary algorithms inspired by natural evolution. The generated population consists of chromosomes (individuals) which are modified with GA operators (crossover and mutation) in order to converge to the solution with the best value of FF. The main steps of GA are (i) initialization of GA parameters; (ii) generation of individuals for an initial population and FF evaluation of the individuals; (iii) selection; (iv) crossover; and (v) mutation. The process is usually repeated until the desired number of generations is reached. GA can be considered slow for finding an optimal solution but it can explore complex space and find values of FF close to the global optimum [15].

B. Particle Swarm Optimization

PSO is considered a biologically based technique of artificial intelligence, inspired by the collective intelligence of swarm (e.g. bird flock, fish school, etc.). The generated population (swarm) consists of individuals (particles) that are adjusting their velocity (2) accordingly to their currently best solution (P_{ld}^t) and based on information obtained in interaction with other individuals (P_{gd}^t). The whole swarm shares the best position of a single particle, as given by (3):

$$V_{id}^{t+1} = W \cdot V_{id}^t + C_1 \cdot r \cdot \left(P_{ld}^t - X_{id}^t\right) + C_2 \cdot r \cdot \left(P_{gd}^t - X_{id}^t\right) \tag{2}$$

$$X_{id}^{t+1} = X_{id}^t \cdot V_{id}^{t+1} \tag{3}$$

where t represents the current iteration, X is the particle position, r is a random number [0,1], C_1 and C_2 are acceleration constants, while W denotes the inertia parameter. PSO represents an efficient global optimization algorithm with fast convergence speed that can be easily implemented. One of the known shortcomings of PSO algorithm is the probability of convergence to the local optimal solution in the early stages of optimization.

C. Grey Wolf Optimizer

Grey Wolf Optimizer (GWO) is a metaheuristic algorithm inspired by behavior of grey wolves. This algorithm mimics the leadership hierarchy and hunting mechanism of grey wolves in nature [12]. The societal hierarchy of the grey wolf pack is divided into four groups (alpha - α, beta - β, delta - δ, and omega). The distance between wolfs in the pack is calculated with (4):

$$\mathbf{D}_a = \left|\mathbf{C}_i \mathbf{X}_\alpha(t) - \mathbf{X}(t)\right|,\ a = \alpha, \beta, \delta;\ i = 1,2,3\ , \tag{4}$$

where **D** represents the distance, **X**(t) is a wolf position in the t-th integration and **C** represents a random number in [0, 2]. Every group has its role in the pack and according to its group status the best FF is defined by alpha, then beta and delta, and the rest of the solutions are considered to be omega. GWO is represented by pack hunting and three main steps are searching for prey; encircling prey; and attacking prey. Position of alpha, beta, and delta leaders are given by (5), while new position of each wolf is updated by (6):

$$\mathbf{X}_1 = \mathbf{X}_\alpha - \mathbf{A}_1\left(\mathbf{D}_\alpha\right),\ \mathbf{X}_2 = \mathbf{X}_\beta - \mathbf{A}_2\left(\mathbf{D}_\beta\right),\ \mathbf{X}_3 = \mathbf{X}_\delta - \mathbf{A}_3\left(\mathbf{D}_\delta\right) \tag{5}$$

$$\mathbf{X}(t+1) = \left(\mathbf{X}_1 + \mathbf{X}_2 + \mathbf{X}_3\right)/3 \tag{6}$$

The GWO saves the best solutions obtained through a defined number of iterations and the goal is to reach prey by the shortest possible route [17].

IV. Fitness Function

In this paper, Fitness Function (FF) provides an assessment of the geometrical alignment of the target and current image. The lower value of FF implies better geometrical alignment, so the goal of BIO is to minimize proposed FF. For evaluating of FF, Sum of Squared Differences (SSD) for two images is used (7):

$$SSD\left(I_1, I_2\right) = \sum_{(u,v)\in I} \left(I_1[u,v] - I_2[u,v]\right)^2, \tag{7}$$

where I_1 and I_2 are the target and current image spatially transformed by TM to match the target image, and u and v are pixel coordinates of given images.

Solution with a minimal value of FF is considered to be an optimal solution. Therefore, appropriate velocities of MR can be computed based on optimally generated elements of TM.

V. Experimental Results Comparison

In this section, the implementation of BIO algorithms (described in Section III) for IR in VS is analyzed. Images used for IR are taken by positioning nonholonomic MR RAICO in poses with known pose displacements given in Table I. RAICO coordinate system is defined according to Fig. 3. A total of 24 images (12 pairs of stereo images) with different displacement from the target images are used for testing of IR.

TABLE I
CURRENT IMAGE DISPLACEMENT COMPARED TO THE TARGET IMAGE

Pair of img.	pose [cm, cm, °]			Pair of img.	pose [cm, cm, °]		
	x	z	θ		x	z	θ
#1	0	+2	0	#7	+2	0	0
#2	0	-2	0	#8	+4	0	0
#3	0	-4	0	#9	+2	-2	0
#4	0	-6	0	#10	+4	-4	0
#5	-4	0	0	#11	0	0	+5
#6	-2	0	0	#12	0	0	-5

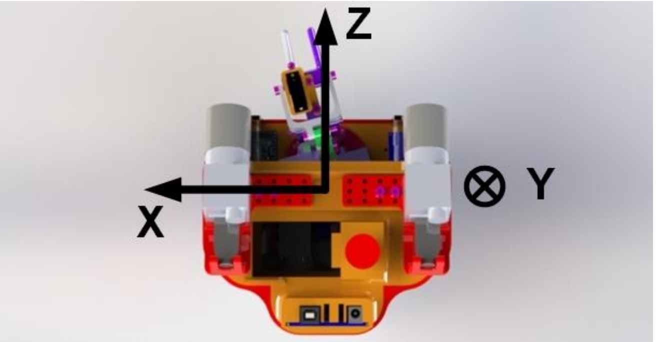


Fig. 3. Coordinate system of nonholonomic mobile robot RAICO

The selection of optimal optimization parameters is done through preliminary experimental parameters tunning. Optimization parameters that are the same for all three BIO algorithms (GA, PSO, and GWO) are: (i) the size of the population – 50, (ii) the maximum number of iterations – 50, and (iv) the number of design variables – 5. For GA, mutation probability is determined by Gaussian distribution, and crossover probability is 0.8. PSO acceleration constants (C_1 and C_2) are set to 2, and the inertia parameter is set to adaptive, with minimum and maximum value of 0.1 and 1.1, respectively. Evaluated design variables are elements of TM (θ, s_X, s_Y, t_X, and t_Y), and their lower and upper bounds are defined as follows:

$$Lb = [-5,\ 0.7,\ 0.7,\ -20,\ -20] \tag{8}$$

$$Ub = [+5,\ 1.2,\ 1.2,\ 20,\ 20] \tag{9}$$

where Lb is lower bound for θ, s_X, s_Y, t_X, and t_Y, respectively, and Ub is upper bound for θ, s_X, s_Y, t_X, and t_Y, respectively.

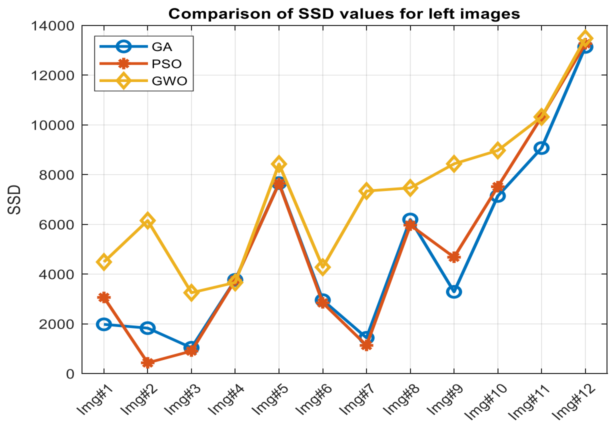


Fig. 4. Comparison of SSD values for left images

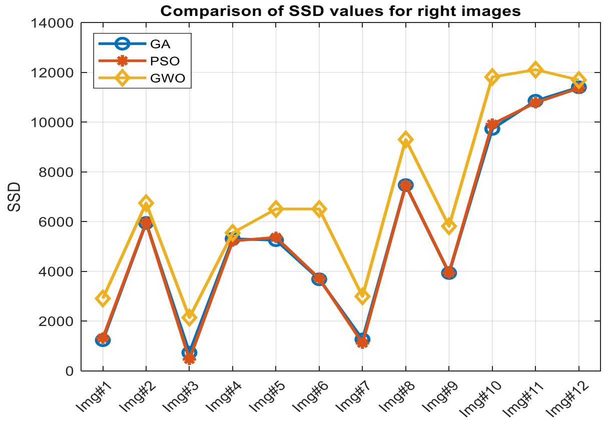
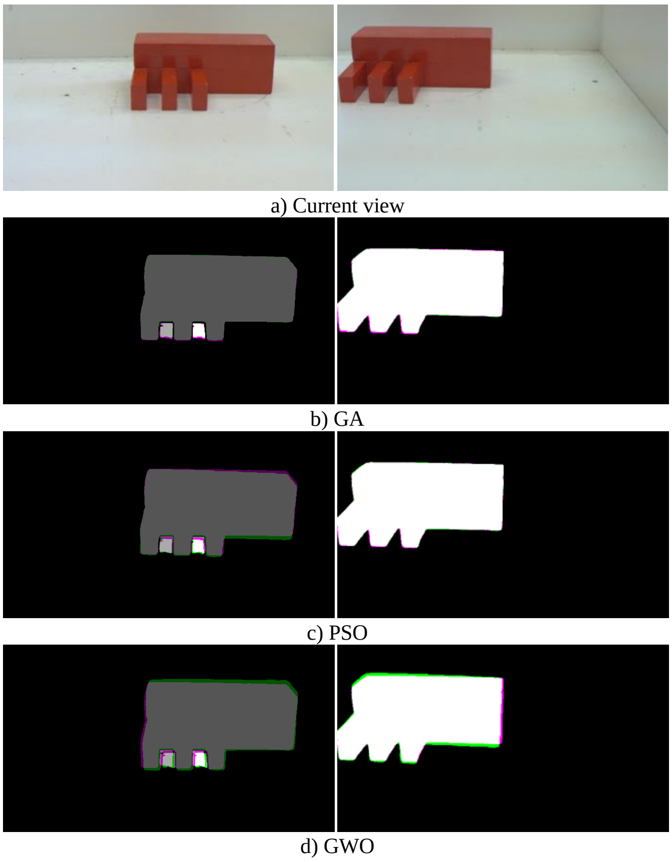


Fig. 5. Comparison of SSD values for right images

Comparison of Sum of Square Differences (SSD) values for left and right images of stereo pairs are given in Fig. 4 and Fig. 5, respectively. It can be observed that with the increase of disparities between the target and current image, the value of SSD steadily increases. Also, for the corresponding left and right stereo pair images, different values of SSD are calculated. In some cases, this occurrence can result in computing different MR velocities for the same camera viewpoints. As it can be seen from Fig. 4 and Fig. 5 the best optimization results are obtained by GA and PSO algorithm, while the worst results in this study are procured by GWO algorithm.



a) Current view

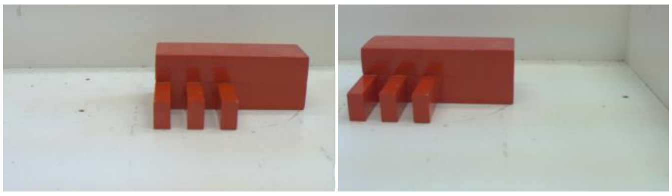
b) GA

c) PSO

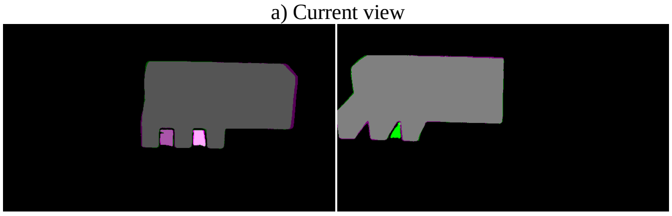
d) GWO

Fig. 6. Comparison of BIO methods for IR – Img#3

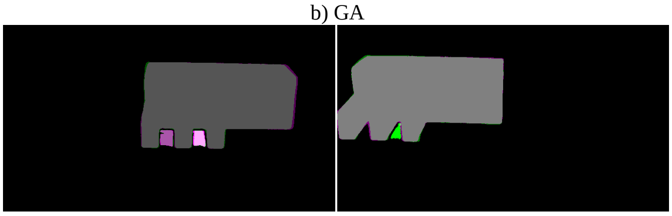
A comparison of geometrical alignment after IR for images #3, images #7, and images #12 with target images (Fig. 2) are given in Fig. 6, Fig. 7, and Fig. 8, respectively. When FF of BIO methods is minimized, elements of TM are evaluated in such a way that the current image can be spatially transformed to overlap with the target image. In Fig. 6 and 7, the overlapping of current and target image is obvious when GA and PSO are utilized. The assessment of satisfactory geometrical alignment is grey and white overlapping, while green and pink colors suggest an unsatisfactory geometrical alignment of current and target image. Fig. 7 shows overall poor geometrical alignment due to inadequate evaluation of TM elements. For both left and right current images, IR for image #10, image #11, and image #12 cannot be considered successful. Large initial displacements have negatively affected the convergence of BIO methods to the global optimal solution. It also should be noted that initial rotation (-5°) about the y-axis in image #12 has caused the manufacturing entity to be only partially seen (Fig. 8a)).



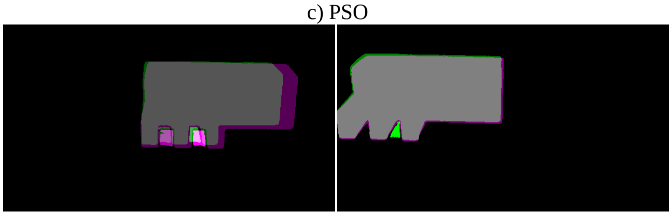
a) Current view



b) GA

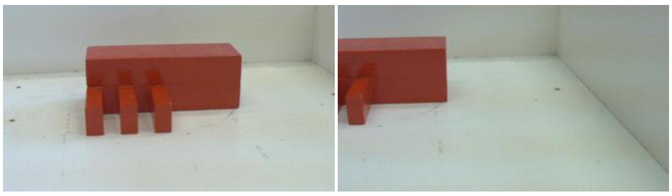


c) PSO

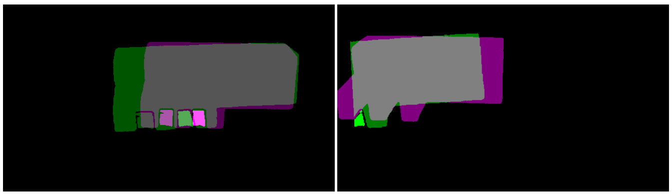


d) GWO

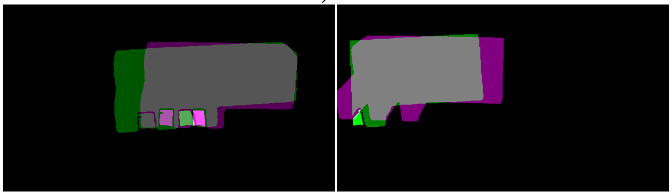
Fig. 7. Comparison of BIO methods for IR – Img#7



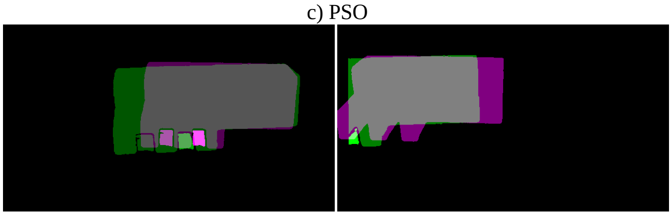
a) Current view



b) GA



c) PSO



d) GWO

Fig. 8. Comparison of BIO methods for IR – Img#12

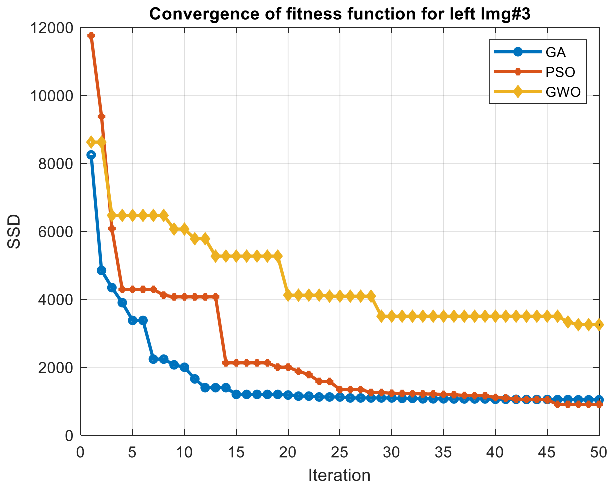


Fig. 9. Convergence of fitness function for left Img#3

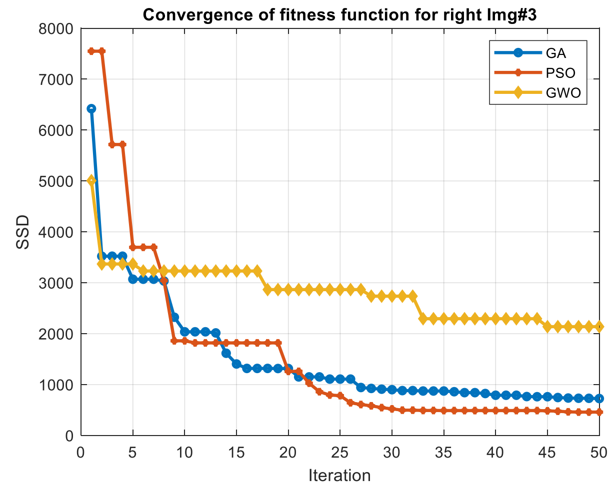


Fig. 10. Convergence of fitness function for right Img#3

For convergence speed comparison of BIO methods image 3 is selected due to the best geometrical alignment (Fig. 9 and Fig. 10). In Fig. 9 results suggest slightly faster convergence speed for GA with similar minimal FF value as PSO, while GWO is heavily outperformed. In Fig. 10 convergence speed is almost identical and the best FF value is in favor of PSO.

Reported results are procured in MATLAB software package running on workstation with Intel i7-7500U 2.7 GHz processor and 16 GB of RAM.

VI. CONCLUSION

In this study, an experimental comparison of three Biologically Inspired Optimization (BIO) methods (Genetic Algorithm – GA, Particle Swarm Optimization – PSO, and Grey Wolf Optimizer - GWO) for Image Registration (IR) is made on a total of 24 images with different initial displacements. The comparison results demonstrate a successful application for minor initial displacements without a change in the orientation of the mobile robot RAICO. The comparison is made on images of manufacturing entities made in a laboratory model of a manufacturing environment. Considering experimental results, the fitness function does not significantly converge after a specific number of iterations, therefore additional stopping criteria can be defined in order to reduce the time required for the optimization process. With the implementation of different strategies for optimization parameters selection we expect to improve achieved results, which represents one of the future work directions. Further work could include an evaluation of other BIO methods for IR, and assessment of various fitness functions.

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