Deploying Swarm Intelligence in Medical Imaging

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Abstract—This paper introduces a novel approach in using a swarm intelligence algorithm – Stochastic Diffusion Search – in medical imaging. After summarising the results of some previous work – showing how the algorithm assists the identification of metastasis in bone scans and microcalcifications on the mammographs – for the first time, the use of the algorithm in assessing the CT images of aorta is demonstrated along with its performance in detecting the nasogastric tube in chest X-ray. The swarm intelligence algorithm presented in this paper is adapted to address these particular tasks and its functionality is investigated by running the swarms on sample CT images and X-rays whose status have been determined by two senior radiologists.

I. INTRODUCTION

Computer aided diagnosis (CAD) is an emerging field in medicine. The technique introduced in this paper can help radiologists examine the image in greater depth and has the potential to help doctors from different medical disciplines to interpret medical imaging with greater confidence. Furthermore CAD is a promising learning tool for both medical students and junior doctors to develop basic diagnostic skills. This paper presents a new CAD approach in which a swarm intelligence algorithm – Stochastic Diffusion Search (SDS) [1] – is applied to four medical imaging modalities.

Understanding the basics behind the behaviour of the swarm intelligence algorithm and its connection to nature is vital. Communication – social interaction or information exchange – observed in social insects is important in all swarm intelligence algorithms, including Stochastic Diffusion Search (SDS), which mimics the recruitment behaviour of one species of ants, Leptothorax acervorum.

There are different forms of recruitment in social insects: it may take the form of local or global, one-to-one or one-to-many, and stochastic or deterministic mode. The nature of information exchange also varies in different environments and with different types of social insects. Sometimes, the information exchange is more complex where, for example, it might carry data about the direction, suitability of the target and the distance; sometimes the information sharing is simply a stimulation forcing a certain triggered action. What all these recruitment and information exchange strategies have in common is distributing useful information in their community.

This paper starts by describing the standard Stochastic Diffusion Search, followed by an introduction to bone scintigraphy, explaining metastatic disease and a brief explanation on how to detect metastasis in bone scans. Next, a brief summary of X-ray mammography and its use is presented, emphasising on mammographic film reading as a particularly demanding visual task, which could be facilitated using the technique presented in this paper.

This is followed by an introduction to aortic aneurysm – is applied to four medical imaging modalities.

A. Previous Work and Summary of Current Research

In the initial work [2], the goal was to visualise the swarms behaviour when presented with a two dimensional canvas (e.g. bone scan). This work was well received as a potential educational tool for doctors in training and medical students. This led to the extension of the research in [3], [4] where
the application of this swarm intelligence technique on bone scan was introduced in further details in different venues for researchers with medical and computer backgrounds. Later in [5], the statistical and mathematical models were presented for bone scans, and the application of the technique was extended to mammography.

In this work, we attempt to present a unifying and generalised framework of the potential of the algorithm, showing its capability in addressing various issues related to different scans and task; after summarising the results of our previous work, two novel applications of the algorithm are introduced:

- The first one is a two-phase process in which initially the swarms identify the location of the aorta within the CT scan. The swarms then set off to detect and highlight any possible calcifications around the aorta with the goal of assisting the radiologists to determine the extent of the calcification. This information can help determine the best possible management of the disease. This task is particularly distinctive from the previous work, as a novel way of guiding the behaviour of the swarms is introduced, increasing their flexibility and functionality.

- The second application introduced in this work is the identification of the tip of the Nasogastric tube in chest X-rays. The significance of the accurate localisation of the tip of the tube is explained with details in this work.

It is vital to note that the presented approach does not attempt to replace the experts’ eyes of radiologists, however in all of the above-mentioned four applications it provides the clinicians with a valuable adjunct to aid with the diagnosis as well as the management of patient. This method of interpreting images can also be used as an educational tool for doctors in training and medical students.

II. Stochastic Diffusion Search

This section introduces Stochastic Diffusion Search (SDS) [1] – a swarm intelligence algorithm – whose performance is based on simple interaction of agents.

The SDS algorithm commences a search or optimisation by initialising its population and then iterating through two phases (see Algorithm 1).

Algorithm 1 SDS Algorithm

01: Initializing agents()
02: While (stopping condition is not met)
03: Testing hypotheses()
04: Determining agents’ activities (active/inactive)
05: Diffusing hypotheses()
06: Exchanging of information
07: End While

In the test phase, SDS checks whether the agent hypothesis is successful or not by performing a hypothesis evaluation which returns a boolean value. Later in the iteration, contingent on the precise recruitment strategy employed (in the diffusion phase), successful hypotheses diffuse across the population and in this way information on potentially good solutions spreads throughout the entire population of agents. In other words, each agent recruits another agent for interaction and potential communication of hypothesis. This algorithm has been used alongside other swarm intelligence algorithms in several research topics including numerical optimisation and clustering.

A. Standard SDS and Passive Recruitment

In standard SDS (which is used in this paper), passive recruitment mode is employed. In this mode, if the agent is inactive, a second agent is randomly selected for diffusion; if the second agent is active, its hypothesis is communicated (diffused) to the inactive one. Otherwise there is no flow of information between agents; instead a completely new hypothesis is generated for the first inactive agent at random (see Algorithm 2). Therefore, recruitment is not the responsibility of the active agents. In this work, activity of each agent is determined when its fitness is compared against a random agent (which is different from the selecting one); if the selecting agent has a better fitness (smaller value in minimisation problems) than the randomly selected agent, it will be flagged as active, otherwise inactive. Higher rate of inactivity boosts exploration, whereas a lower rate biases the performance towards exploitation.

Algorithm 2 Passive Recruitment Mode

01: For ag = 1 to No_of_agents
02: If ( !ag.activity() )
03: r_ag = pick a random agent()
04: If ( !r_ag.activity() )
05: ag.setHypothesis( r_ag.getHypothesis() )
06: Else
07: ag.setHypothesis( randomHypothesis() )
08: End If/Else
09: End If
10: End For

III. Bone Scintigraphy

Bone scan or Bone scintigraphy is one of the most frequently performed of all radionuclide procedures. Radionuclide bone imaging is quick, relatively inexpensive, widely available, exquisitely sensitive and is invaluable in the diagnostic evaluation of numerous pathologic conditions. Although protocols vary among institutions, imaging is typically performed 2–6 hours after intravenous administration of technetium-99m–labeled diphosphonates. The delay between injection and imaging allows clearance of the radiotracer from the soft tissues, resulting in a higher target-to-background ratio and improved visualization of bone. The degree of radiotracer uptake depends primarily on two factors: blood flow and, perhaps more importantly, the rate of new bone formation [6].

A. Metastatic Disease

Metastasis is the process by which the cancer spread from the original site at which it started as a primary tumour to other tissues in the body i.e. Prostate cancer metastatising to the bone tissue.

When the metastatic process is diffuse, virtually all of the radiotracer is concentrated in the skeleton, with little or no activity in the soft tissues or urinary tract. The resulting pattern,
which is characterized by excellent bone detail, is frequently referred to as a superscan (see Fig. 1 Top-right) [7], [8], [9].

IV. MAMMOGRAPHY

X-ray mammography has been shown to be effective as a method for detecting early breast cancer, but the success of mass screening depends critically on the availability of highly skilled film readers to interpret the images. The majority of film readers in the UK are consultant radiologists and in order to maintain a sufficiently high standard of interpretation, readers are required to undergo training, to keep in practice and to evaluate their performance at regular intervals [10].

V. AORTIC ANEURYSM DISEASE

The aorta is the main artery that carries the blood away from the heart to rest of the body giving rising to various branches for this purpose. Aortic aneurysm (AA) is a disease commonly found in patients above the age of 65. It is defined as a permanent localized dilation of the aorta that has at least a 50% increase in diameter as compared with the expected normal diameter of the aorta, which may vary according to age, sex, and body size [11]. The primary goal in Aortic Aneurysm treatment is to prolong survival through the prevention of rupture. The treatment options include the following [11]:

- Open surgical repair
- Endovascular repair (EVAR)
- Continued surveillance

The pre-EVAR anatomical evaluation assesses several aspects of the anatomy of the aortic aneurysm including the proximal neck of aneurysm anatomy as is the most important predictor factor for a successful EVAR. The proximal neck is the segment of aorta above the aneurysm sac. An unfavourable neck anatomy, based on its diameter, length, angulation, morphology, and presence of calcification and mural thrombus, is the most frequent cause of exclusion from EVAR [12].

VI. NASOGASTRIC TUBE

Nasogastric tubes (tube inserted through the nose to the stomach) are commonly used for short-term nutrition in critically ill patients. Complications of nasogastric tubes frequently include inadvertent malpositioning and aspiration pneumonia that may cause severe harm or death. The National Patient Safety Agency (NPSA) in the United Kingdom received reports of 21 deaths and 79 cases of harm due to feeding into the lungs though misplaced NG tubes between September 2005-March 2011 [13]. The main cause of the harm in the investigated cases was the misinterpretation of the X-rays that were done to assess the position of the NG tube (see Fig. ??).

The careful interpretation of an X-ray to assess the position of an NG tube needs a trained eye. This might not be available at all times. This limitation in resources may lead to either misinterpretation by a junior doctor leading to a serious clinical incident or if there is a delay in the interpretation this can translate itself to a delay in feeding the patient for several hours. The SDS can help provide a tool to avoid the above scenarios by detecting the tip of the NG tube.

VII. APPLYING STOCHASTIC DIFFUSION SEARCH

In this paper, we are presenting a unique approach by deploying SDS to use in assessing medical images. This
A. Algorithm Procedure

SDS is a population based stochastic algorithm, adapted here to search for areas of metastasis or calcifications in the feasible solution space. The hypothesis vectors of the population are defined as follows:

\[
x^g = [x^g_{i,1}, ..., x^g_{i,D}], \quad i = 1, 2, ..., NP
\]

where \( g \) is the current iteration, \( D \) is the dimension of the problem space \( (D = 2) \) and \( NP \) is the population size. In the first generation, (when \( g = 0 \)), the \( i^{th} \) vector’s \( j^{th} \) component could be initialised as:

\[
x^0_{i,j} = x_{\min,j} + r(x_{\max,j} - x_{\min,j})
\]

where \( r \) is a random number drawn from a uniform distribution on the unit interval \( U(0, 1) \), and \( x_{\min}, x_{\max} \) are the lower and upper bounds of the \( j^{th} \) dimension, respectively. The initial status of all agents are set to false. In other words, each agent randomly picks a pixel from the image of the scan.

During the test phase of SDS algorithm, each agent’s status should be determined. The method used here to set the activity of the agents is to find the average of the colour intensity\(^1\) \( \text{avgIn} \) of each agent and its neighbours (Fig. 4). If \( \text{avgIn} \) is within a specific range (problem dependent), the agent is flagged active, otherwise inactive.

During the diffusion phase, each inactive agent randomly selects another agent from the population; if the selected agent is active, the selecting agent adopts the hypothesis (i.e. location) of the active agent and the information sharing takes place. The strategy used for information sharing is to randomly pick an area surrounding the active agent (see Fig. 5). Active agents also check their position by continuously picking a random pixel in the neighbourhood; this way, an area which does not have a good enough potential is discarded from one iteration (i.e. cycle of test and diffusion phases) to the next.

B. Bone Scans

This section presents the results focusing on bone scans; however the methods used are extendible to other scans referred to in this work.

Below are the adjustable parameters that are determined depending on the problem in hand (i.e. identifying metastasis in bone scan) and the machine used to generate the scans. In this experiment, they are defined as:

- \( S = 10,000 \)
- \( \alpha = 180. \)
- \( \text{dRad} = 2 \)
- \( \text{Itr} = 10 \)

As shown in Fig. 1, areas with higher potential of metastasis are identified. In bone scans, other than urinary bladder activity, faint renal activity, and minimal soft-tissue activity which are normally present in the scan (Fig. 1 Bottom-left), the existence of multiple, randomly distributed areas of increased uptake of varying size, shape, and intensity are highly suggestive of bone metastases (Fig. 1 Bottom-middle). Additionally as stated before, when the metastatic process is

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\(^1\) Colour intensity \((In)\) signifies the brightness of pixels, \(0 \leq In \leq 255\).
distributed, almost all of the radiotracer congregates in the skeleton, with little or no activity in the soft tissues or urinary tract (see Fig. 1 Bottom-right).

As shown in Fig. 1 and 2, areas with higher potential of metastasis and calcifications are identified. In bone scans, other than urinary bladder activity, faint renal activity, and minimal soft-tissue activity which are normally present in the scan (Fig. 1 Bottom-left), the existence of multiple, randomly distributed areas of increased uptake of varying size, shape, and intensity are highly suggestive of bone metastases (Fig. 1 Bottom-middle). Additionally as stated before, when the metastatic process is distributed, almost all of the radiotracer congregates in the skeleton, with little or no activity in the soft tissues or urinary tract (see Fig. 1 Bottom-right).

In order to visually present the technique used, Fig. 7 illustrates how agents congregate over the areas of interest over time (i.e. iterations) when fed with the scans as inputs of the algorithm. As the figure shows, successful agents diffuse their positions across the population and this way, information on potentially good solutions spreads throughout the entire population of agents. This process is caused through the recruitment strategy, where each agent recruits another agent for interaction and potential communication of the promising areas. Next, two models are presented to distinctively differentiate between different types of bone scans (e.g. not affected, affected and highly affected).

1) Statistical Model: Here, a statistical analysis, TukeyHSD Test [14], is performed to highlight whether there is a significant difference between the activity of the agents when processing the bone scans. Table I (a) shows the activity rate of the populations over each iteration. Three different samples are used for this analysis: Samples 1, 2 and 3 refer to the scans in Fig. 1 (left to right). Table I (b) shows that other than the first iteration where the agents are just initialised, different bone scans would result in significantly different activity rates. This could be used as an indicator, highlighting the difference between various scans and whether they are healthy, partially affected or the metastasis is spread.

2) Mathematical Model: Visualising the data produced in Table I (a) could introduce another method of determining which of the three broad category (healthy, partially affected or the metastasis is spread) the bone scan falls into (see Fig. 8). This model is proposed here to calculate the first and the second derivatives using the following formulas:

\[ f'_{i} = \sigma_{i}^{s} - \sigma_{i-1}^{s} \]

\[ f''_{i} = \sigma_{i}^{s} - 2 \times \sigma_{i-1}^{s} + \sigma_{i-2}^{s} \]

where \( f' \) and \( f'' \) are the first and the second derivatives respectively, \( \sigma \) represents the number of active agents, \( i \) is the iteration number and \( s \) is the bone scan sample number, \( s = \{1, 2, 3\} \). The value of the second derivative \( (f'') \) can be used as an indicator to stop the algorithm. The rationale behind stopping the algorithm is that the activity of the agents has reached a point that allowing further process, would blur the congregation of the agents around less popular clusters. This is caused by the diffusion mechanism of the algorithm where there is higher probability of an inactive agents picking another one from within the larger clusters than the smaller ones.

Having discussed the functions of statistical and mathematical methods, the following three sections extends the use of SDS to mammographs, AAA’s CT scans and NG-tube’s X-ray.

C. Mammographs

One of the main aims of the CAD systems is to identify microcalcifications to help the radiologists make the diagnosis. Microcalcifications are sometimes difficult for the human film reader to detect because of their small size and low contrast, particularly if they are superimposed on dense glandular tissue. However, of all the signs of abnormality found on mammograms, microcalcifications are the easiest to detect automatically. Unlike small ill-defined masses, which may superficially resemble normal glandular tissue, microcalcifications have properties namely their very small size and high attenuation which differ significantly from those of normal background structures.

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**TABLE I. ACTIVITY STATUS OF AGENTS PROCESSING BONE SCANS**

(a) Mean ± standard deviation of the number of active agents in each iteration is shown (rounded to the nearest number).

<table>
<thead>
<tr>
<th>It</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>1</td>
<td>5 ± 2</td>
<td>17 ± 4</td>
<td>277 ± 16</td>
</tr>
<tr>
<td>2</td>
<td>15 ± 4</td>
<td>47 ± 9</td>
<td>763 ± 37</td>
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<tr>
<td>3</td>
<td>33 ± 8</td>
<td>100 ± 18</td>
<td>1602 ± 76</td>
</tr>
<tr>
<td>4</td>
<td>66 ± 18</td>
<td>201 ± 31</td>
<td>2991 ± 137</td>
</tr>
<tr>
<td>5</td>
<td>129 ± 33</td>
<td>379 ± 51</td>
<td>4992 ± 188</td>
</tr>
<tr>
<td>6</td>
<td>245 ± 62</td>
<td>697 ± 84</td>
<td>7260 ± 198</td>
</tr>
<tr>
<td>7</td>
<td>461 ± 110</td>
<td>1250 ± 141</td>
<td>8947 ± 123</td>
</tr>
<tr>
<td>8</td>
<td>852 ± 201</td>
<td>2201 ± 230</td>
<td>9583 ± 51</td>
</tr>
<tr>
<td>9</td>
<td>1557 ± 351</td>
<td>3650 ± 330</td>
<td>9708 ± 22</td>
</tr>
</tbody>
</table>

(b) Based on TukeyHSD Test, if the difference between each pair of samples is significant, the pairs are marked (o – X shows that the right sample has significantly more active agents than the left one). This test uses 95% family-wise confidence level.

The aim is to show that agents dealing with scans which have different levels of metastasis exhibit significantly different behaviour.
Adjustable parameters:

- \( S = 10,000 \)
- \( \alpha = 120 \). As discussed earlier, this experiment requires a higher level of sensitivity and thus the threshold of \( \alpha \) is set lower than the previous experiment.
- \( \beta = 140 \)
- \( d\text{Rad} = 2 \)
- \( \text{Itr} = 10 \)

Since smaller clusters are of interest in bone scan and specially mammographs, a different mechanism for determining the ‘stopping point’ is proposed. In this method, when \( f'' < 0 \) the algorithm reaches the stopping point. Fig. 2 shows that areas with higher potential of calcifications.

D. Aortic Aneurysm Disease

The SDS algorithm is utilised in this experiment to assess the proximal neck of the aneurysm and detect the level of calcification above the sac. The agents are initialised throughout the search space (i.e. the CT image) in a two-phase mission, the first of which is to identify the location of the aorta within the scan, and the second phase highlights the existing calcification within the marked area. The adjustable parameters are empirically chosen as follows in each phase.

Phase one:

- \( S = 1,000 \)
- \( \alpha = 100 \)
- \( \beta = 140 \)
- \( d\text{Rad} = 3 \)
- \( \text{Itr} = 50 \)

Phase Two:

- \( S = 1,000 \)
- \( \alpha = 150 \)
- \( \beta = 255 \)
- \( d\text{Rad} = 1 \)
- \( \text{Itr} = 100 \)

In the first phase, since the radius of the area of interest is in one particular area (i.e. aorta, which exists in only one place in each scan), the diffusion phase is set to explore a bigger region of the search space around the active agent and thus the diffusion radius, \( d\text{Rad} \) is set to 3 units (see Fig. 5). This leads to the identification of the centre of aorta which is presented in Fig. 10 top.

Fig. 10 middle highlights the region where potential calcifications could be spotted by the swarms (within the bigger circle in the figure); once this region is located, the second phase commences where swarms congregate over the area of interest based on the value of \( \alpha < \text{avgIn} < \beta \), which dictates the activity of the swarm and thus the convergence behaviour as shown in Fig. 10-bottom. As indicated above, in the second phase, the algorithm is allowed a smaller diffusion radius, \( d\text{Rad} \), but a larger number of iterations in order to ensure a total convergence of the swarms to more precise areas with the required colour intensity.

Once the swarms converge, the suitability of the scan is evaluated by measuring the activity rate of the swarms; this activity is directly related to the level of calcification in the aortic wall in that particular segment of the aorta. This helps comparing different parts of the aorta to choose the best possible location with the least level of calcium in the wall of the proximal neck to position the EVAR graft.

This can help assess CT angiography images of patients awaiting the repair of the aortic aneurysm. The SDS can evaluate all the CT slides that did look at the proximal neck to
reduce the risk of the proximal type I endoleak. This type of endoleak is the most serious complication of EVAR and it is a life threatening problem. When this occur the aneurysm sac is not excluded from the circulation and it can get larger and rupture causing a vascular catastrope with 50-75% mortality rate.

**E. Nasogastric Tube**

In this experiment the SDS agents are applied to identify the tip of the NG tube that is the most radiopaque part. This can help clinicians identify the distal end of the tube and assess its position to ensure that it is in the stomach and not in the lungs (see Fig. 11).

The adjustable parameters for this experiment are:

- \( S = 10,000 \)
- \( \alpha = 240 \)
- \( \beta = 250 \)
- \( d_{rad} = 2 \)
- \( Itr = 10 \)

The last three sections argue for the generalisation of the swarm intelligence technique presented in this paper. While the authors strongly keep themselves away from the any claim that the presented technique could replace human experts, the sample applications of this technique, shows the usefulness of the method and its possible potential to reduce human error and assist the identification of metastasis and micro-calcifications in various types of scans.

**VIII. Conclusion**

This paper details the promising results of the novel application of Stochastic Diffusion Search in detecting areas of metastasis in bone scans and the identification of the potential microcalcifications on the mammographs. Statistical and mathematical models are proposed to further investigate the behaviour of the agents in the population and the outcome demonstrates that the algorithm exhibits a statistically significant difference when applied to scans of variously affected individuals.

The swarms intelligence technique was also used in the two-phase process of the identification of aorta in the CT
Fig. 10. Top: identifying the location of the diseased aorta within the scan; Middle: highlighting areas where potential calcifications might exist; Bottom: identification of calcification on the current slide of CT scan in order to compare with the others

images, as well as calcifications in areas around the aorta; this task could lead to a more accurate localisation of the neck of the aneurysm.

Additionally, the swarms exhibited promising performance in detecting the tip of Nasogastric tube inserted through the nose to the stomach with the goal of providing short-term nutrition in critically ill patients. The identification of the tip of the tube by the swarms can in practice lead to reducing the probability of the complications of nasogastric tubes frequently caused by inadvertent malpositioning of the tube in the lungs versus stomach.

At last not least, the authors would like to emphasise that the presented technique could be effectively utilised as an adjunct to the expert’s eyes of a specialist.

REFERENCES


