

Theses of Doctoral (PhD) Dissertation

**Enhanced ensemble-based object detection in
medical image analysis**

László Kovács

Dissertation supervisor: Dr. Lajos Hajdu



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1 Introduction

Medical imaging has improved considerably and contributed to the creation of remarkable achievements in disease treatment over the past decades. Nowadays it is completely general to use medical imaging in everyday medical practice to support non-invasive or semi-invasive medical interventions. Thanks to the technical progress of computers, digitization of imaging brought in a new era in the field of medical imaging. The digitized data are storing, and improved technology allows to create more accurate and precise treatments. At the same time, the larger world population causes an increased demand for medical treatment, which stimulates the era of automatization in medical imaging. In the recent years, the technology-driven developments to provide better medical services are rapidly going. Despite the clear progress, medical image processing is a non-trivial task and is one of the most widely researched fields. Due to the increasing size and diversity of data obtained by better and better sensors, the most important challenges in this field are the complexity of the image processing problems and the computation times of their algorithmic solutions. To reduce complexity and raise the accuracy of the solutions, splitting the problem into subtasks is a known answer. The detection of the location of an object on an image is one of the most common tasks in the field of medical image processing. In this task, a classification procedure of the image pixels is solved with the help of classifiers. The reason for composing ensembles from individual classifiers is to make joint classification from the aggregated data instead of using only one classifier. These ensembles are popular to use since they can increase the accuracy of the final answer and make it possible to apply existing research results. For decision making, majority voting is a usually applied model. Although the ensembles can reduce the complexity in the level of sub-tasks,

the complete ensemble-based software solution mostly has great computational demand.

During the thesis work, I focused on the investigation of ensemble-based image processing involving optimization which increases the accuracy and decreases the computing time. In the dissertation, novel results are reported about ensemble based enhanced object detection, including extension, optimization of the ensembles. The solutions also respond to high-performance computing demands.

The structure of the thesis work is the following. In chapter 2, a novel ensemble-based combined object detection algorithm is introduced. Based on the applied theoretical model of the proposed method, it is studied in chapter 3 how to improve the performance of ensemble-based object detection further by adding a classifier. Chapter 4 contains comprehensive examinations about optimization of ensemble-based methods. Namely, in section 4.1, the generalized diversity-based ensemble optimization results are described. To follow the ensemble optimization consideration, a new approach is presented in section 4.2 to compose an ensemble with maximal performance under certain constraints. Finally, in section 4.3 a hardware-based solution with optimal task scheduling is given for ensemble-based system, in a high-performance computing environment.

In the followings I briefly summarize the contents of my dissertation focusing on my own contributions. For details and all the related issues (literature reviews, methodologies, data description. etc.) see the dissertation.

2 Combined object detection of optic disc and macula based on anatomical features

In the chapter 2 of the dissertation, I introduce an efficient combination of algorithms for the automated localization of the optic disc and macula in retinal fundus images. There is in fact no reason to assume that a single algorithm would be optimal. An ensemble of algorithms based on different principles can be more accurate than any of its individual members if the individual algorithms are doing better than random guessing. I aim to obtain an improved optic disc and macula detector by combining the prediction of multiple algorithms, benefiting from their strength and compensating their weaknesses. The location with a maximum number of detectors outputs is formally the hotspot and is used to find the optic disc or macula center. I developed a flexible framework for combining state-of-the-art OD/macula detectors. An assessment of the performance of integrated systems and detectors working separately is also presented. I show that this combination outperformed all the individual algorithms. I use a majority voting and weighted linear combination based scheme that counts the number of outputs of the algorithms falling in a disc of a specified radius.

Thesis 1.: I developed a combined object detection method based on anatomical features, using a generalized majority voting model. I constructed the weight function for its application to detect optic disc and macula. By the help of experiments using public databases, I showed that the method outperforms both the individual algorithms, and their combination using the classical majority voting.

Corresponding publications: [1–9]

3 Extending an ensemble-based system with an additional classifier

In chapter 2 of the dissertation, I presented a joint object detection fusion based system. As decision rule, I apply a generalized spatial constrained majority voting for each detected object extended with a combined final decision driven by anatomical features. Although the object detectors as classifiers with adequate performance level are essential, they need to have advantage connected to group work environment also. That is, besides natural abilities like performance and running time; the behavior conducted dependency in a complex system is important, too. It is not hard to see that the brute-force approach way extension could lead a fusion system performing below the expectation regarding computational complexity, running time and in particular of system performance. In that context, I address to find an adequate dependency among classifiers with low running time. Instead of the highest performance of the algorithms, the goal is to optimize our complete system to regarding *pattern of success* and *pattern of failure* which are such realizations of the votes in a series of experiments that lead to the possible highest and lowest accuracy of the ensemble.

So the chapter 3 of the dissertation, the first aim is to investigate how changes the system performance if a new classifier is added to the system. While the joint model is deterministic thanks to the anatomical features and obviously depends in particular on the performance of the separate detection, I study the separate behavior. I describe our generalized model working behind the separate object detection. The basis of the generalization is the introduced p_{nk} model to handle spatial majority voting regarding independency and dependency. A possible way to get the p_{nk} values is to determine them experimentally, both in the dependent and in the independent cases to characterize

the performance changes of our application. I do this in order to investigate and characterize what is the possibility to make some further improvements the accuracy level of the ensemble by the help of more classifiers. I can characterize how to affect the system performance if a new classifier is added to the system. Based on the results it is obvious that our classifiers in a fusion system do not act as independent voters. My system works very efficiently with high level performance, according to the experimental outcome.

since the result showed its performance is very close to the optimum. Nevertheless, if it would contain completely independent classifiers, it could work more effectively. However, it is unclear whether it is possible to reach the complete independence while all the classifiers nominate candidates based on the same data source (input images) only.

Thesis 2: I developed a method to characterize and measure the improvability of the accuracy of a generalized ensemble-based object detection system. I adopted the theoretical results for a medical application.

Thesis 2.1: Based upon the theoretical results, by the help of experiments using a public image database, I showed that a specific set of optic disc classifiers is dependent. I described the accuracy of every subset of the elements of the ensemble.

Thesis 2.2: Based on the theoretical results, by experiments on publicly available image databases, I obtained the minimal and maximal values of the accuracy of a generalized ensemble-based optic disc detection method in the following cases:

- *a new independent algorithm is added to a dependent system;*

- *a new independent algorithm is added to an independent system;*
- *a new dependent algorithm is added to a dependent system.*

Corresponding publications: [1, 3–7]

4 Ensemble-based system optimization

4.1 Composing an ensemble-based system guided by diversity measures

In the section 3 of the dissertation it is presented how the classical majority voting model can be extended to the spatial domain e.g. to solve object detection problems. As it is also pointed out, the detector algorithms cannot be considered as independent classifiers in applications, so a good ensemble cannot be composed by simply selecting the individually most accurate members. Whereas it is identified the limits of the performance regarding the extension capability, the level of dependency among classifiers remains unknown. Moreover, in the section 3 in the dissertation, it was proved by a heretical based investigation that there is dependency in our example object detection application. The aim is to describe the dependency to improve the selection efficiency of classifiers towards composing more performance optimized ensemble compared with which is composed by simply selecting the individually most accurate members. In classic theory, diversity measures are recommended to help to explore the dependencies among the classifiers. Therefore, I generalize the well-known statistical diversity measures for our generalized majority voting as a general tool for ensemble optimization in two steps. Firstly, I show how classic pairwise measures can be extended to explore larger sets of classifiers via letting the contingency table entries of an ensemble-based system be freely weighted. Secondly, I introduce these extended measures also to the spatial domain within a majority voting framework. These generalized diversity measures can be use with classic majority voting and other multidimensional investigations of diversity. In experiments, I show that it has better performance in case of the classic majority. As a more specific use of diversity measures, I

introduce extended measures for the spatial constraint majority voting framework. I show experimentally that these measures fit better to spatial applications with a specific example of optic disc detection. Moreover, I show also how a more efficient descriptor could be found in terms of a weighted combination of diversity measures which correlates better with the accuracy of the ensemble. In the experimental test, I use the publicly available database.

Thesis 3.: I generalized the standard two-dimensional diversity measures of the classical majority voting to the higher dimensional case. My experiments show that the generalized diversity measures outperform the original ones, i.e., they provide better estimates for the ensemble accuracy.

Corresponding publications: [10]

Thesis 4.: I generalized the higher dimensional diversity measures of the classical majority voting to be applicable in the case of spatial constraint voting. By the help of experiments, I justified that the generalized diversity measures outperform the original ones, i.e. they give better estimates for the ensemble accuracy.

Corresponding publications: [10]

Thesis 5.: I described a method to compose an ensemble with maximal performance, based on the generalized diversity measures. Using the theoretical results, I constructed the best performing combination of a given set of classifiers in a concrete application concerning the detection of the optic disc.

Corresponding publications: [10]

4.2 Composing an ensemble-based system guided by a constraint

There are many possibilities to improve the performance of ensemble-based systems further. One possibility is to adjust the free parameters of the members to provide maximal ensemble accuracy. High ensemble accuracy is a generally fundamental requirement. However, other performance issues might be reasonable. One such specific point is the execution time since ensembles are more resource demanding in this respect: they have to execute all their members before making their decision. Within a specific total execution time, one cannot achieve a considerable increase in system accuracy by adding new members to the ensemble. For this aim, I consider both the execution time and accuracy of each member. Then, I solve the problem on how to find the most accurate ensemble, where the sum of the execution times of its members remains below the limit. As a decision rule, I maximize a majority voting-based energy function that is applicable in single object detection scenario. This optimization task leads to a non-separable knapsack problem, which is addressed by stochastic considerations. I solve this combinatorial optimization task by a stochastic approach through formulating knapsack problems with an energy function based on the majority voting rule. I plot in chapter 4.2 of the dissertation the ensemble accuracy against the time limit for several cases, which may help a user to select an appropriate time limit, where the accuracy reasonably increases. Moreover, it also becomes possible to see whether the acceleration of specific components may raise ensemble accuracy. As a real experimental study, I consider a single object detection scenario for the localization of the optic disc in retinal images. In this way, I also compare our models for independent systems with a real one having dependencies among its members. Though the independent models help to measure the expected behavior, the extension of the study seems to be

reasonable for dependent systems, as well.

Thesis 6.: I introduced a method for the optimal composition of ensembles under the constraint that the total computational time is limited. For this, I generalized the knapsack problem using a majority voting energy function and solved the combinatorial optimization task by a stochastic approach. Applying the theoretical results, I developed an algorithm to compose an ensemble with maximal performance regarding execution time constraint in the optic disc medical application.

Corresponding publications: [11]

4.3 Ensemble-based systems in HPC environment

Recently, serious efforts have been made to improve the performance of medical image analysis methods using ensemble-based systems. An ensemble-based system has high-performance computing demand. I present a novel hardware-based solution for the efficient adoption of our complex, fusion-based approaches for real-time applications in the chapter 4.3 of the dissertation. Even though most of the image processing problems and the increasing amount of data have high-performance computing (HPC) demand, there is still a lack of corresponding dedicated HPC solutions for several medical tasks. To widen this bottleneck, I have developed a Hybrid Small Size high-performance computing Resource (abbreviated as HuSSaR; For more details see also HuSSaR webpage¹.) which efficiently alloys CPU and GPU technologies, mobile and has an own cooling system to support easy mobility and wide applicability. Besides a proper technical description, I include several practical examples from clinical data

¹https://arato.inf.unideb.hu/kovacs.laszlo/research_hybridmicrohpc.html

processing domain in this work. These computations of the complex, fusion-based approaches have been optimized to fit HPC environment. The optimal exploitation of the system is demonstrated on a skin lesion classification, CT segmentation and 3D visualization including virtual reality tasks and the third party application SWhybrid. The task schedulers (grid engine/slurm) manage task assignments to hardware so that the hardware acceleration is driven by optimal task scheduling based on task hardware requirement and maximize the utilization of the hardware. Our distributed parallelized complex fusion based retinopathy screening system included the described model above also competed on ISBI 2018 Diabetic Retinopathy – Segmentation and Grading Challenge and passed out with good marks.

Thesis 7.: I provided a hybrid hardware-based solution for optimal task scheduling of complex algorithms and composed ensembles in HPC environment. I introduced a method to find the optimal scheduling with respect to the computational requirements of the individual algorithms, in various applications.

Corresponding publications: [12–18]

Összefoglalás (summary in Hungarian)

Ebben a fejezetben, tézispontokba szedve összegezzük a diszsertációban bemutatott eredményeket.

1. *Tézis: Kifejlesztettem egy többségi szavazás elvén működő, anatómiai képletek tulajdonságait is figyelembe vevő több objektum együttes detektálását megvalósító eljárást. Kidolgoztam az eljárás végső jelöltpár (sárgafolt - vakfolt) súlyfüggvényét. Publikus adatbázisokon történő kísérletek segítségével megmutattam, hogy a kidolgozott módszer nemcsak az egyéni algoritmusoknál, hanem a klasszikus többségi szavazást használó összetett rendszernél is hatékonyabb.*
Kapcsolódó publikációk: [1–9]
2. *Tézis: Módszert adtam egy objektumdetektáló általánosított összetett rendszer kibővítésekor történő teljesítményváltozás mérésére és a teljesítmény javítására. Az elméleti eredményeket sikerrel alkalmaztam egy valós orvosi képfeldolgozási problémában is.*
 - 2.1. *Tézis: Az elméleti eredmények alapján, egy publikus adatbázison végrehajtott kísérletek segítségével igazoltam egy konkrét osztályozórendszer függőségét. Sikerült a rendszer valamennyi részrendszerének teljesítményét is meghatároznom.*
 - 2.2. *Tézis: Az elméleti eredmények alapján, publikus adatbázison végrehajtott kísérletek segítségével meghatároztam az általánosított vakfolt detektáló összetett rendszer teljesítményének minimális és maximális értékét a következő esetekben:*

- *függtelen algoritmussal bővítünk egy függő rendszert;*
- *függtelen algoritmussal bővítünk egy független rendszert;*
- *függő algoritmussal bővítünk egy függő rendszert.*

Kapcsolódó publikációk: [1, 3–7]

3. *Tézis: Kiterjesztettem a klasszikus többségi szavazó modellek esetén használatos kétváltozós diverzitás mérőszámokat magasabb dimenziós esetre. Kísérletek segítségével igazoltam, hogy a kiterjesztett mérőszámok teljesítményben felülmúlják az eredeti mérőszámokat, azaz pontosabb becslést adnak az összetett rendszer pontosságára.*

Kapcsolódó publikációk: [10]

4. *Tézis: Kiterjesztettem a magasabb dimenziós diverzitás mérőszámokat térbeli többségi szavazó modellekre. Kísérletek segítségével igazoltam, hogy a kiterjesztett mérőszámok térbeli szavazás esetén teljesítményben felülmúlják az eredeti mérőszámokat, azaz pontosabb becslést adnak az összetett rendszer pontosságára.*

Kapcsolódó publikációk: [10]

5. *Tézis: Kidolgoztam egy, az általánosított mérőszámokon alapuló módszert maximális teljesítményű összetett rendszer összeállítására. Az elméleti eredményeket valós orvosi alkalmazásba átültetve, egy konkrét algoritmusrendszerből kiválasztottam a vakfolt meghatározására szolgáló maximális teljesítményű algoritmuskombinációt.*

Kapcsolódó publikációk: [10]

6. *Tézis: Módszert adtam a maximális teljesítményű részrendszer meghatározására a számítási erőforrások korlátozása*

mellett. Ehhez a többségi szavazó energiafüggvény segítségével általánosítottam a hátizsák problémát, és arra egy sztochasztikus megközelítésű kombinatorikus optimalizációs meg-oldást adtam. Az elméleti eredmények felhasználásával algoritmust fejlesztettem egy korlátozott futási idejű, maximális teljesítményű, vakfolt megkeresésére szolgáló összetett rendszer konstrukciójára.

Kapcsolódó publikációk: [11]

7. Tézis: Hardver alapú megoldást adtam a komplex algoritmusok és összetett rendszerek optimális ütemezésére hibrid szuperszámítógépes környezetben. Több alkalmazás esetén megmutattam, hogyan valósítható meg az egyes algoritmusok számítási igénye szerinti optimális ütemezés.

Kapcsolódó publikációk: [12–18]

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Candidate: László Kovács
Neptun ID: EV3E3L
Doctoral School: Doctoral School of Informatics
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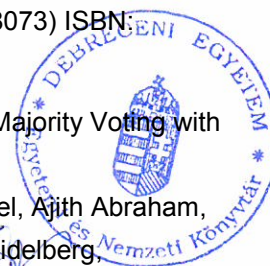
List of publications related to the dissertation

Hungarian book chapters (1)

1. **Kovács, L.**, Pintér, Á.: Stirling számok vizsgálata HPC környezetben.
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Patents (1)

22. **Kovács, L.**, Hajdu, A., Harangi, B., Sós, A.: Hybrid Small Size hpcResource - HuSSaR

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Under consideration

List of other publications

Foreign language Hungarian books (1)

23. Hajdu, A., Qureshi, R. J., Pető, T., Nagy, B., **Kovács, L.**, Harangi, B.: Detection of the optic disc and the macula through combining algorithms. Faculty of Informatics, Debrecen, 17 p., 2010. (Technical Report ; 7. Preprints ; 380.)

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