A Survey of Selected Algorithms Used in Military Applications from the Viewpoints of Dataflow and GaAs

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Abstract

This is a short survey of ten algorithms that are often used for military purposes, followed by analysis of their potential suitability for dataflow and GaAs, which are a specific architecture and technology for supercomputers on a chip, respectively.

Whenever an algorithm or a device is used in military settings, it is natural to assume strict requirements related to speed, reliability, scale, energy, size, and accuracy. The two aforementioned paradigms seem to be promising in fulfilling most of these requirements.

1 Introduction

This is a mini survey of ten specific algorithms for optimization and learning, combined with an analysis of their suitability for dataflow implementations in future supercomputers on a chip, as described in \cite{1}, and their suitability for GaAs technology, which is also an option for future supercomputers on a chip.

In section 2, each algorithm is specified with appropriate mathematical and logical notions, and presented using the guidelines from \cite{2}, which means the following:

1. What is the problem to be solved.
2. What was the best existing algorithm prior to the introduction of the presented one.

3. Why the newly proposed algorithm is better?

4. How much is it better and under which conditions?

Each of the above issues is presented as concisely as possible to provide an effective insight into the essence.

In section 3, each algorithm is described from the viewpoint of its suitability for dataflow technology, which is of interest for high-speed, high-precision, low-power, and low-size applications in aerospace and defense.

In section 4, each algorithm is described from the viewpoint of its suitability for GaAs technology, which is of interest for ultra-high-speed processing in high radiation environments, typical of aerospace and defense.

Section 5 presents conclusions related to the price/performance ratio for various scenarios of interest for this survey.

The last part includes references. Four of them are general, while the others are related to the ten surveyed algorithms.

## 2 Algorithms

Artificial intelligence (AI) and algorithms in general have made their way into the area of defense, where their widespread use is changing the classical doctrines of warfare and defense in general. Algorithms are used in detection, planning, field operations, and support functions, which are the main tasks in the defense sector. Algorithms and smart sensors are used to detect potentially dangerous persons and objects at border crossings, customs checkpoints, and other ports of travel. The insights gained as outputs of these algorithms are used to deploy active policing and provide a more holistic understanding of crisis scenarios. In planning, available data and algorithms are used to better anticipate resourcing requirements and associated costs for missions and training exercises. In field operations, these can provide real-time information and quick assessment to improve mission outcomes, protect people, assets, and information. Some systems and weapons are equipped with various support and decision-making systems while unmanned vehicles and robots perform tasks that involve safety risks with high accuracy and fewer resources.

In this paper we present ten algorithms that are used in military applications for core, tactical, and support operations. Instances of underlying
problems, i.e., inputs for algorithms, are usually large in scale. Therefore, there is a large amount of data that need to be processed fast, preferably in real time, accurately and reliably, while guaranteeing confidentiality and control of information even when operating in adverse conditions.

The most frequently found algorithms in DARPA sponsored projects are related to the problems and algorithms that we are presenting below. The selection of algorithms and problems seems to be slightly biased towards computer vision for it seems to be the essential technology for the development of autonomous vehicles, replacing the driver’s eye, thus allowing the vehicle to detect objects of interest in dangerous locations.

2.1 Large-scale stochastic programming problems

There are plenty of optimization problems occurring on a daily basis in the military with some uncertainties that are usually represented as scenarios. Applications range from scheduling monthly or daily air or sea lifts with uncertain cargo [3], to cyber workforce planning [4] or planning of medical facility deployment [5]. These need fast, accurate, and reliable solvers of large-scale stochastic programming problems.

*Benders decomposition* is a mathematical programming technique for solving very large linear programming problems with specific block structure [6]. Suppose that a problem occurs in two or more stages, where the decisions for the later stages depend on the results from the previous ones. The first attempt to make a decision for the first stage problem is performed without prior knowledge of optimality regarding later stage decisions. The first stage decision is the master problem, whereas subsequent stages are considered as separate subproblems whose information is passed back to the master problem. If any violation of a constraint of a subproblem is detected, the constraint is added back to the master problem, which is then resolved. The master problem represents an initial convex set which is further constrained by information gathered from the subproblems hence shrinking the feasible space as information is added. If matrices \(A\) and \(B\) represent the constraints, and \(Y\) represents the feasible set of \(\tilde{y}\), the problem we are solving is represented as a minimization problem as follows
minimize $\bar{c}^T \bar{x} + \bar{d}^T \bar{y}$
subject to $Ax + By \geq \bar{b}$
$y \in Y$
$\bar{x} \geq \bar{0}$

Linear programming in general is an NP-complete problem and Benders decomposition is a method that slowly converges to the desired solution. It decomposes the problem into a large number of smaller problems that are essentially polynomial-time computable while their independence allows for efficient use of parallelism.

2.2 Image registration

The absolute accuracy of robotic arms and autonomous armored vehicles is possible thanks to computer vision applied on high-resolution inputs gathered from multiple cameras which ultimately need to be transformed into the same coordinate system to create consistent data for subsequent algorithms. This is done using the so-called image registration algorithm.

Image registration involves spatially transforming the source image(s) to align with the target image. The alignment is performed using a specific mapping called homography which is defined as follows.

Let $(x, y)$ be a 2D point in an image. It can be represented as a 3D vector $\bar{x} = (x_1, x_2, x_3)$, where $x = x_1/x_3$ and $y = x_2/x_3$ which is actually a point on a projective plane. Let $f(x, y)$ and $f'(x, y)$ be two images. We need to estimate a transformation $T$ such that

$$f(x, y) = f'(T(x, y)).$$

There is a plethora of algorithms that accurately perform image registration. When images are exposed to noise causing a scene to appear cluttered in an image, the best existing solution has polynomial time complexity (see [7]).

2.3 Video stitching

Image and video stitching is the process of removing the limitations of the field of vision in an image or video by stitching several multiple overlapping images/videos to obtain a wide field of image/video view. Video stitching
is essentially a generalization of a multi-image stitching with a new set of 
constraints and challenges.

First, images need to be transformed into the same coordinate system 
using previously explained image registration. Then, depending on the use 
case, an appropriate algorithm is chosen to find the seams of the stitches.

Faster and earlier developed algorithms usually perform global defor-
mation and alignment of multiple overlapping images according to an es-
timated single transformation. Recently developed algorithms transform 
the problem into more advanced optimization problems that consider cam-
ena movement, which requires stabilization of the video. Video stitching 
can therefore be posed as optimizing an objective function consisting of a 
stabilization term and a stitching term on which an iterative optimization 
algorithm is performed. Clearly, vast amount of computation is required 
even for stitching low-resolution videos (see [8]).

### 2.4 Pattern recognition algorithms

Pattern recognition is concerned with automatic identification of regularities 
in data and classifying data into different categories.

Formally, given an unknown function \( g : \mathcal{X} \rightarrow \mathcal{Y} \) (the ground truth) that 
maps input instances \( \mathbf{x} \in \mathcal{X} \) to output labels \( \mathbf{y} \in \mathcal{Y} \), along with training 
data \( \mathbf{D} = \{(\mathbf{x}_1, y_1), \ldots, (\mathbf{x}_n, y_n)\} \) assumed to represent accurate examples 
of the mapping, produce a function \( \mathbf{h} : \mathcal{X} \rightarrow \mathcal{Y} \) that approximates the correct 
mapping \( g \) as closely as possible.

**Classification** is the problem of identifying to which of a set of categories 
(sub-populations) an observation (or observations) belongs. Examples for 
this are labeling an identified object on a video stream as an enemy, or 
assigning a device in a network a diagnosis based on observed characteristics 
of the device (type, presence of certain features, etc.). For the classification 
problem we will consider logistic regression, kNN, perceptrons, and SVM.

**Clustering** is a method for classifying and predicting categorical labels, 
and for this category we will present the k-means algorithm.

Finally, we will also consider the *ensemble learning*, whose essence are 
supervised meta-algorithms for combining multiple learning algorithms to- 
gether.

#### 2.4.1 Logistic Regression

The logistic model is used in statistics to assess the probability of a certain 
event or an existing set of them such as pass/fail, win/lose, alive/dead, or
enemy/friend. It can also be extended to model several classes of events such as determining if a person in an image has an RPG or not, if an image contains a specific object, etc. Each object detected in an image is assigned probability between 0 and 1, with the sum of one.

Formally, consider a single training data point \((x, y)\) and set

\[
P(Y = 1 | X = x) = \theta_0 + \sum_{i=1}^{m} \theta_i x_i.
\]

Now, using the maximum likelihood estimator or even the Newton method, find the values of \(\theta_i, i = 0, 1, \ldots, m\), that maximize the probability for all the data.

Calling \(n\) the size of a training sample and \(m\) the number of weights, training will take \(O(m^2 n + m^3)\) steps and prediction \(O(m)\) steps.

### 2.4.2 Online kNN

kNN is a supervised learning algorithm that stores the labeled trained examples given as pairs \((X_1, Y_1), (X_2, Y_2), \ldots, (X_n, Y_n)\) taking values in \(\mathbb{R}^d \times \{1, 2\}\).

Training stage consists of just storing these samples. To make a prediction, kNN algorithms find the \(k\) nearest neighbors of a query point and compute the class label based on the \(k\) nearest most similar points.

To compute distance to one example \(O(d)\) steps are needed. \(O(nd)\) steps are needed to find the nearest neighbor. \(O(nkd)\) steps are needed to find \(k\) closest examples. This is is prohibitively expensive for a large number of samples.

Faster and real-time execution of this simple algorithm requires suitable parallelization such as in [9].

### 2.4.3 Perceptron

The perceptron is an algorithm for learning a threshold function: a function that maps its input \(x\) (a real-valued vector) to output value \(f(x)\) (a single binary value)

\[
f(x) = \begin{cases} 1 & \text{if } \mathbf{w} \cdot \mathbf{x} + b > 0, \\ 0 & \text{otherwise} \end{cases}
\]

where \(\mathbf{w}\) is a vector of real-valued weights, \(\mathbf{w} \cdot \mathbf{x} = \sum_{i=1}^{m} w_i x_i\) where \(m\) is the number of inputs to the perceptron, and \(b\) is the bias which shifts the decision boundary away from the origin and is independent from the input.
The perceptron learning algorithm needs exponential time, though there are algorithms requiring $O(n^{7/2})$ steps.

A natural extension of the single-layer perceptron described above is the multilayer perceptron which essentially contains many perceptrons organized into layers thereby gaining in the ability to solve more complex problems in reasonable time.

### 2.4.4 Neural networks for real-time object detection

A reliable and highly accurate real-time object detection algorithm is of paramount importance in defense. Its goal is to detect instances of semantic objects of a certain class (such as humans, animals, roads, or vehicles) in a given video in real-time. The input is given in the form of a continuous video stream, and the output is given as a tuple of annotated descriptors assigned to each detected object bounded by an appropriate box in the frame in which it appears.

The YOLO algorithm, presented in [10] is considered state of the art algorithm. The processing pipeline of YOLO comprises a single neural network which first predicts bounding boxes in images, after which the problem is reduced to regression on spatially separated bounding boxes.

The military application of this approach imposes two additional constraints: (1) no trade-offs between accuracy and speed, and (2) not using networks pretrained outside the security perimeter for security reasons.

These constraints and the nature of the problem require huge continuous processing power over a flow of data for these algorithms to be used.

### 2.4.5 Support Vector Machine (SVM)

To detect intrusions (IDS) in a network, its traffic is analyzed for particular signatures. Normal network traffic often exhibits a similar signature to attacks, and hackers often apply obfuscation for network intrusion.

Machine learning offers a wide range of efficient tools for accurately identifying an IDS, with a restriction that training datasets should not be associated with malicious data. The Support Vector Machine (SVM) is a promising candidate for this task [11].

This algorithm aims to find a hyperplane in the $N$-dimensional space that separates data points while keeping the maximum margin, that is, maximum distance between the points of individual classes. Formally, suppose that we are given a training dataset of $n$ points $(\vec{x}_1, y_1), (\vec{x}_2, y_2), \ldots, (\vec{x}_n, y_n)$, where $y_i \in \{-1, 1\}$ denotes the class that $\vec{x}_i$ belongs to. The goal is to find
the hyperplane which divides points \( \vec{x}_i \) for which \( y_i = 1 \) from those for which \( y_i = -1 \), whereas the distance from the nearest point \( \vec{x}_i \) to the hyperplane is maximized.

Even though the space and the time complexity of SVM are polynomial (quadratic and cubic on the size of the input respectively), the amount of data in a network calls for special architecture for this algorithm to be efficiently used for the aforementioned purpose.

### 2.4.6 k-means

k-means clustering is a method of vector quantization, that aims to partition \( n \) observations into \( k \) clusters, whereby each observation belongs to the cluster with the nearest mean, serving as a prototype of the cluster. This results in a partitioning of the data space into Voronoi cells.

Given a set of observations \( \mathbf{x} = (\vec{x}_1, \vec{x}_2, ..., \vec{x}_n) \), where each observation is a \( d \)-dimensional real vector, k-means clustering aims to partition \( n \) observations into \( k \), \( k \leq n \) sets \( S = \{S_1, S_2, ..., S_k\} \) so as to minimize variance within the cluster.

Formally, the objective is to find:

\[
\arg\min \sum_{i=1}^{k} \sum_{\mathbf{x} \in S_i} \| \mathbf{x} - \mu_i \|^2,
\]

where \( \mu_i \) is the mean of points in \( S_i \).

The problem is computationally difficult (NP-hard); however, efficient heuristic algorithms quickly converge to the local optimum for most problem instances.

### 2.4.7 Ensemble modeling – boosting

Ensemble modeling uses multiple different modeling algorithms or different training datasets to predict an outcome. The ensemble model then aggregates the prediction of every used model and derives its final prediction for unseen data. In particular, boosting is a kind of ensemble modeling that has been widely used in military applications (see [12]).

A boost classifier is a classifier

\[
F_T(x) = \sum_{i=1}^{T} f_i(x)
\]
where each $f_t$ is a “weaker” classifier that takes object $x$ as input and returns a value indicating the class of the object.

Each of these classifiers produces an output hypothesis, $h(x_t)$, for each sample in the training set. At each iteration $t$, a weak classifier is selected and assigned coefficient $\alpha_t$ such that the sum of the training error $E_t$ of the resulting $t$-stage boost classifier is minimized.

In practice, AdaBoost algorithm is realized by cascading the number of SVM weak classifiers described above.

3 Dataflow

The dataflow paradigm [13, 14, 15] has been introduced as contrast to the traditional controlflow paradigm [16]. In controlflow, a program is written with the intention to micro-control the flow of data through hardware. In dataflow, a program is written with the intention to configure hardware, so that, in the ideal case, voltage difference can move data through hardware.

The dataflow paradigm can achieve speedups of 10x, 100x, or even 1000x, compared to the controlflow paradigm. At the same time, power reduction can be about 10x. Precision can be varied throughout the algorithm, which saves chip area. The size of equipment also gets reduced with a factor of up to 10x.

The algorithms that benefit the most from this paradigm are those characterized by time-consuming loops and lots of data usability within each particular loop iteration. Among the algorithms surveyed in this article, the most suitable ones for dataflow implementation are: logistic regression, k-means, and ensemble modeling.

Examples of dataflow implementations of these algorithms, as well as other similar ones, can be found at appgallery.maxeler.com or in [13]. For more information, interested readers are referred to references [16, 14, 15].

4 GaAs

GaAs technology can also be used for design of processors and implementation of algorithms. It offers significantly higher processor speed and level or radiation hardness, which makes it suitable for use in aerospace and defense environments. On the other hand, the number of transistors that can be placed on a single chip is smaller, while gate delay heavily depends on the gate fan-out.
These characteristics define the specific requirements of processor design and algorithm implementation. On one hand, not much logic could be placed onto a single chip, and on the other hand, the ratio of off-chip to on-chip delays is relatively high. This mandates the utilization of highly pipelined architectures in which pipeline elements are of a relatively small complexity.

Efforts to implement various types of processors, under DARPA sponsorship, were described in [17] and [18]. Important concepts were described in [19] and [20]. These concepts are also relevant also for the implementation of algorithms described in this article.

Based on the facts given above, it follows that the most effective implementations can be expected from algorithms that can be implemented using many small elements, connected in a pipelined fashion like image/video registration and stitching. Other examples include perceptron, SVM, k-means, and ensemble modeling. These statements were verified through a number of student projects at the universities where the coauthors of this article teach.

5 Conclusions

The surveyed algorithms were chosen by the frequency of usage in selected military applications. They have been studied from the viewpoint of their implementation based on the dataflow paradigm and GaAs technology.

It has been found that some algorithms are better suited for dataflow than others. Namely, the best suited ones are those characterized by a high contribution of loops to the overall run time, as well as those with a high level of data reusability within each loop iteration.

As far as the potential benefits coming from the utilization of GaAs technology, the best performance increases are expected from those algorithms that can be implemented on a large number of small modules, connected in a pipelined or systolic fashion. Furthermore, the algorithms being less sensitive to large ratios of off-chip to on-chip delays are better suited for this technology, which offers high speedups, but does not permit large chips.

Finally, this survey opens new research avenues related to the synergies in the triangle: algorithms – architectures – technologies. To make an appropriate selection of a specific algorithm from a plethora of options, it is necessary to conduct an analysis of the kind presented in this article.
References

[1] Veljko Milutinović, Erfan Sadeqi Azer, Kristy Yoshimoto, Gerhard Klimeck, Miljan Djordjevic, Milos Kotlar, Miroslav Bojovic, Bozidar Miladinovic, Nenad Korolija, Stevan Stankovic, et al. The ultimate dataflow for ultimate supercomputers-on-a-chip, for scientific computing, geo physics, complex mathematics, and information processing. In 2021 10th Mediterranean Conference on Embedded Computing (MECO), pages 1–6. IEEE, 2021.

[2] Veljko Milutinovic. The best method for presentation of research results. IEEE TCCA Newsletter, pages 1–6, 1996.

[3] Javier Salmeron, R Kevin Wood, and David P Morton. A stochastic program for optimizing military sealift subject to attack. Military Operations Research, pages 19–39, 2009.

[4] Nathaniel D Bastian, Christopher B Fisher, Andrew O Hall, and Brian J Lunday. Solving the army’s cyber workforce planning problem using stochastic optimization and discrete-event simulation modeling. In 2019 Winter Simulation Conference (WSC), pages 738–749. IEEE, 2019.

[5] Lawrence V Fulton, Leon S Lasdon, Reuben R McDaniel Jr, and M Nicholas Coppola. Two-stage stochastic optimization for the allocation of medical assets in steady-state combat operations. The Journal of Defense Modeling and Simulation, 7(2):89–102, 2010.

[6] Jacques F Benders. Partitioning procedures for solving mixed-variables programming problems. Numerische mathematik, 4(1):238–252, 1962.

[7] Heng Yang and Luca Carlone. A polynomial-time solution for robust registration with extreme outlier rates. arXiv preprint arXiv:1903.08588, 2019.

[8] Wei LYU, Zhong ZHOU, Lang CHEN, and Yi ZHOU. A survey on image and video stitching. Virtual Reality & Intelligent Hardware, 1(1):55–83, 2019.

[9] David Marquez-Viloria, Luis Castano-Londono, and Neil Guerrero-Gonzalez. A modified knn algorithm for high-performance computing on fpga of real-time m-qam demodulators. Electronics, 10(5):627, 2021.
[10] Joseph Redmon, Santosh Divvala, Ross Girshick, and Ali Farhadi. You only look once: Unified, real-time object detection. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2016.

[11] Kinan Ghanem, Francisco J. Aparicio-Navarro, Konstantinos G. Kyriakopoulos, Sangarapillai Lambotharan, and Jonathon A. Chambers. Support vector machine for network intrusion and cyber-attack detection. In 2017 Sensor Signal Processing for Defence Conference (SSPD), pages 1–5, 2017.

[12] Wassim Ben Chikha, Slim Chaoui, and Rabah Attia. Performance of adaboost classifier in recognition of superposed modulations for mimo twrc with physical-layer network coding. In 2017 25th International Conference on Software, Telecommunications and Computer Networks (SoftCOM), pages 1–5, 2017.

[13] Veljko Milutinović, Jakob Salom, N Trifunović, and Roberto Giorgi. Guide to dataflow supercomputing. Springer Nature, 10:978–3, 2015.

[14] D Milutinovic, V Milutinovic, B Soucek, and B Estell. The open channel. Computer, 20(04):81–83, 1987.

[15] Michael J Flynn, Oskar Mencer, Veljko Milutinovic, Goran Rakocevic, Per Stenstrom, Roman Trobec, and Mateo Valero. Moving from petaflops to petadata. Communications of the ACM, 56(5):39–42, 2013.

[16] Milo Tomasevic and Veljko Milutinovic. Hardware approaches coherence in shared-memory multiprocessors, part 1. IEEE Micro, 14(05):52–59, 1994.

[17] Veljko Milutinovic. Guest editor’s introduction gaas microprocessor technology. Computer, 19(10):10–13, 1986.

[18] Walter Helbig and Veljko Milutinovic. A dcfl e/d-mesfet gaas experimental risc machine. IEEE transactions on computers, 38(2):263–274, 1989.

[19] Veljko Milutinovic and Noe Lopez-Benitez. A gaas-based microprocessor architecture for real-time applications. IEEE transactions on computers, 100(6):714–727, 1987.
[20] Veljko Milutinovic, David Fura, and Walter Helbig. An introduction to gaas microprocessor architecture for vlsi. *Computer*, 19(03):30–42, 1986.