Spinal Cord Simulation for Chronic Pain Management: Towards an Expert System

Kenneth M. Aló[1], Richard Aló[2], Andre de Korvin[2],
and Vladik Kreinovich[3]

[1]Pain and Health Management Center
17270 Red Oak, Suite 275
Houston, TX 77090

[2]Center for Computational Science and
Advanced Distributed Simulation
University Houston-Downtown
One Main Street, Houston, TX 77002
emails ralo@uh.edu, dekorvin@dt3.dt.uh.edu

[3]Department of Computer Science
University of Texas at El Paso
El Paso, TX 79968
email vladik@cs.utep.edu

Abstract

Chronic pain is a serious health problem affecting millions of people worldwide. Currently, spinal cord simulation is one of the most effective methods of easing the chronic pain. For most patients, a careful selection of weak electric currents enables to drastically decrease the pain level. The first devices offered only a few possible regimes, and it was possible to choose an appropriate regime simply by exhaustive search. Continuous engineering progress leads to more and more flexible devices that offer a wide variety of millions of possible simulation regimes. With this variety, it is no longer possible to test all of them on each patient, we need an intelligent *method of choosing an appropriate simulation regime.*

In this paper, we describe the design of an expert system for choosing appropriate simulations. We hope that our paper will be understandable both for the computer science readers interested in medical applications, and for medical researchers interested in using computers for pain relief.

1 The problem

Chronic pain: a problem. Pain is unpleasant, but it serves an important goal: it signals to the brain that something is wrong with a certain part of the body. The intensity of pain is usually proportional to the importance of the signal: severe pain indicates a life-threatening situation that needs an immediate help (like chest pain during the heart attack), while a minor pain (e.g., caused by a small cut) usually indicates a relatively minor problem.

Unfortunately, the pain-generating mechanism itself is as prone to mis-perform as any other physiological mechanism in our bodies. Ideally, we should get a pain signal in the presence of damage, and no pain signal if there is no damage. If the pain mechanics mis-performs, we can get one of the two errors:

- there is a damage, but no pain is felt;
- there is no serious damage, but a severe pain is felt.

Situations of the first type mainly require caution, frequent tests, etc. (e.g., people with diabetes, usually, do not get any indication of the low sugar count until it may be life-threatening, so they must continuously monitor their sugar count). In short, these situations are manageable.

Situations of the second type are much more serious: they lead to a continuous strong pain (*chronic pain*) that is not an indication of any physiological damage. Chronic pain is a serious health problem that affects up to 10% of the world population (more than 25 million of people in the United States only). Chronic pain may not be perceived as such a threat as cancer or heart diseases because, unlike these diseases, it does not kill. However, chronic pain disables more people than cancer or heart disease. It costs the US economy more than $90 billion per year in medical costs, disability payments, and lost productivity.

To ease the suffering of the patients suffering from the chronic pain, it is desirable to stop the pain signals from being received by the brain. This is a very difficult task because, although we can monitor the signals coming through the neurons, the existing technology is not capable of differentiating between neuron impulses that correspond to pain and other types of neural impulses. Since the physiology of pain is still at its infancy, we need some indirect *heuristic* methods to get rid of the pain.

Easing chronic pain: a brief history. Since pain signals are simply electric signals, it is natural to use electricity to treat chronic pain.

The use of electricity to treat chronic pain has its roots in the ancient world: Roman physicians prescribed the use of "electric fish" in the treatment of their first century patients. The modern use of electricity to treat pain began in the 1750's, when European researchers experimented with newly-invented mechanical devices capable of producing static electricity. The invention of the electrochemical battery in 1800 led to improved treatments. By 1826 guidelines for the use of direct current in medical treatment had been published. The use of electrostimulation gradually diminished after 1900, when the credibility of the treatment was undermined by unsupported claims of earlier researchers.

Easing chronic pain: the idea of Spinal Cord Stimulation (SCS) and its current achievements. The problem of easing chronic pain is made somewhat easier by the fact that all the pain signals, no matter where they originate, go through the *spinal cord* before they reach the brain. So, the idea is to surgically insert electrodes attached to different points on the spine, and then apply a trial-and-error method to find the combination of signals that would eliminate or at least ease this pain.

This idea was known for quite some time, but it was only implemented in the 1960's, because the implementation of this idea is not easy at all: we want to target the pain in a certain area and so, we need to find the place on the spine that corresponds to this very area of the body. This place is usually very small and difficult to find.

The first clinical trials of this idea were not always successful: Following the *gate control* theory, by Melzack and Wall in 1965, Shealy *et al.*, and Wall and Sweet published first clinical reports of pain relief by direct spinal cord stimulation in 1967. Many inappropriate patients were subsequently implanted and large numbers of failures resulted.

During the 1970's significant improvements in technology occurred, resulting in greater success. In 1973, Cook published favorable responses in multiple sclerosis patients. Shimoji developed a catheter type electrode in 1974. Waltz developed a laminotomy type electrode for clinical applications. In 1979 quadrapolar electrode catheters were introduced.

In the 1980's technology continued to advance, as did the types of conditions identified for treatment using SCS. Surgical instruments were refined and better radiological imaging equipment led to the procedure becoming more widely used. The first multi-programmable electronics were introduced in 1980, and totally implantable neural stimulator systems were introduced in 1981. Eight-channel multiprogrammable electronics and the first eight-electrode catheter were developed in 1986. In 1988 the non-invasive programmable implantable pulse generator that also had radio frequency capabilities was introduced.

In the 90's as patients with more complex conditions were identified, use of multi-lead electrode arrays was adopted. As a result, implantable programmable pulse generators, implantable radio frequency receivers, and more sophisticated objective patient screening methods have led to improved outcomes.

Easing chronic pain by SCS: main problems. In spite of the successes of Spinal Cord Stimulation in easing chronic pain, there are still several unsolved problems:

- First, there are, currently, only a few medical doctors knowledgeable and qualified enough to perform these procedures. It is desirable to use the knowledge of these doctors for creating a software helping tool that will help other doctors apply similar techniques. One of the possibilities is to design a computer-based simulator to help the doctors learn this technique.

- Second, the current adjustment procedures take too long. In the academic environment, where a doctor can spend dozens of hours with each patient, the success rate is very high: in the majority of cases, there is a drastic pain relief. However, in the clinical environment, we cannot afford to spend that much time with each patient. It is, therefore desirable to design a special computer-based tool that would speed up this adjustment phase. Since each adjustment requires a feedback from the patient, we need, therefore, a computer-based simulation tool that would help the patient to speed up the learning process.

- Finally, although the existing combinations of signals help to ease the pain in the majority of the patients, with some patients, there is no drastic pain relief, and even if there is, it is desirable to eliminate the pain altogether. For that purpose, medical engineers are currently developing a new generation of implanted tools that would enable us to drastically increase the variety of different signals sent to the spine and thus, hopefully, increase the possibility that some combination of these signals will help every patient. But with this variety comes a problem: we cannot any longer test all possible combinations of these signals (there are more than 40 million possible combinations), so we need to design an intelligent method of finding the best combination without going through all of them.

What we are planning to do. In this paper, we describe a design of an expert system whose goal is to solve these problem.

- From the *computer science* viewpoint, all the main implementation ideas are already there, so in this sense, the design of the system is almost ready.

- However, the actual implementation for medical purposes requires extreme caution and doublechecking, so, from the *medical* viewpoint, it is still largely the work in progress.

In the following sections, after a brief technical overview, we will follow the pain-relief process stage by stage; for each stage, we will describe how this stage is performed at present, what are the main problems, and how our expert system will help in solving these problems.

2 Current technique: a brief technical overview

Lead. This is typically a round 1.5 to 2 mm diameter catheter 60 cm long, with 4 to 8 electrodes (electrical contact points).

The lead is inserted into the epidural space of the spine through a hollow needle which is inserted through the skin and between spinal vertebrae. All placement activity is performed through the use of a *fluoroscope* (active X-ray) for visualization. The crude placement is guided by physiological properties of the body along with historical, published recommendations. All fine adjustment is performed strictly through trial and error testing during surgery, using the awake patient as the feedback mechanism.

Receiver or **IPG** (**Implantable Pulse Generator**). The other component which is implanted in the body is the device responsible for delivering the electrical charge. In both types of devices (IPG and Receiver) a "pocket" is made approximately 1/4″ under the skin in an area agreed to by the patient and physician for comfort and effectiveness. The "terminal" end of the lead(s) is(are) routed (or tunneled) under the skin from the spine exit point to the pocket. The lead(s) and receiver/IPG are connected, placed in the pocket, and the pocket closed.

Comment. As indicated, multiple leads may be connected to the receiver/IPG allowing the activation and control of up to 16 electrodes.

Transmitter. This component only applies to a Radio Frequency (RF) system utilizing an implanted receiver. The transmitter is worn externally and transmits energy and programs to the receiver via an attached antenna which is placed directly over the receiver. A primary benefit of this system is that the transmitter can be customized through a computer driven interface.

Determining the Prescription. For purposes of this discussion we will term an SCS prescription as one in which the patients pain is relieved to the greatest extent possible. However, before any treatment can be prescribed the physician must know where the patient feels pain. The best method for documenting this is visually using an anatomical diagram. Currently there are two methods for doing this:

- the standard method, in which a patient uses paper and pencil; and

- utilization of a computer program with a pen or with some other drawing interface.

Once the physician knows what areas of the body need treatment, he/she can then determine the system to be implanted, the prospective spinal entry point, and subsequent electrode position.

Determining the optimal stimulation settings is a little bit more difficult. All SCS systems require adjustment to the following electrical parameters in order to effect stimulation:

Polarity. Sometimes we need positive electrical stimulation, sometimes a negative stimulation is better. So, each of the 4 to 16 controllable electrodes can be in one of the two possible polarities: $+$ and $-$.

Pulse width. Current systems allow pulse widths to be adjusted from 10 to 500 microsecond (μs).

Frequency. Current systems allow frequency to be adjusted from 10 to 1500 Hz.

Amplitude. The electrical energy delivered for simulation is proportional to the pulse amplitude (voltage). Current systems allow a typical range of 0.1 V to 12.0 V.

Electrode placement. As stated previously, refined electrode placement is performed in the operating room (OR) with the patient alert (in order to provide the necessary feedback). Placement testing involves the following factors (which are combined to select the best placement):

- Human interpretation of the fluoroscope (X-ray) image.
- Selection of electrode polarities expected to "target" a specific pain site.
- Selection of frequency and pulse width which is known to be advantageous for OR testing.
- Adjustment of amplitude until the patient indicates sensation.
- Anatomical description of where the sensation(s) is (are) felt.

The result of the feedback determines: whether another test should be performed, whether the lead should be moved, whether parameters (polarity) should be changed, or whether several of these things should be modified.

3 First stage: surgical implanting of electrodes

3.1 How this is currently done

At first, we must surgically insert the electrodes. There are two basic ways of doing it:

- it can be a serious surgery, in which an incision is made and electrodes are surgically attached to the spinal cord; or
- electrodes are attached through special needles, via a more minor surgical procedure.

In both situations, there are rules that describe, depending on the pain location, where approximately we need to place the electrodes. The resulting locations often do not lead to exactly the points that are connected with the targeted pain locations, so, usually, these locations need some adjustment based on the patient's reaction.

3.2 The problems

Some rules are not explicitly formulated. Some of the rules for the original (approximate) placement and for the further adjustment have not been explicitly formulated. It is desirable to explicitly formulate all of them and to check that the resulting set of rules is indeed sufficient, that no implicit "common sense" rules (that are very clear to the experts but that may be not clear at all for new doctors) have been missed.

Rules are formulated in terms of natural language. Even those rules that have been formulated are often formulated not in mathematically precise terms, but rather by using terms from natural language like "lower the position a little bit". Since different people may understand these terms differently, it is desirable to re-formulate these rules in precise terms.

In addition to the rules, we want to use the experience of successful surgeries. In addition to the rules, we may want to use a database that contains the experience of successful surgeries. This database may contain some information that the current experts are unable to explicitly articulate.

3.3 Our approach

We need an expert system. We face the situation in which there are a few experts who formulate their knowledge in terms of rules (often imprecise) and who are willing to make their knowledge more available. We want to produce a computer-based system that would help other users make similar decisions. Such systems that incorporates the experts' knowledge are called *expert systems.* So, our goal is to design an *expert system* that incorporates the expert's rules about placing the electrodes.

We need an expert system with fuzzy rules. One of the problems is to describe the knowledge that is currently represented by words of *natural language* in formal terms understandable by a computer. The best method of doing it is by using a special formalism that was specifically designing for formalizing this "linguistic" knowledge: *fuzzy logic* (see, e.g., [4, 6, 11]). So, the designed expert system is based on fuzzy logic.

The optimal choice of a fuzzy logic. In this design, we will use the expertize that we gained in NASA applications of fuzzy logic control: namely, it turned out that some versions of fuzzy logic are most appropriate when we are looking for the smoothest possible control, while others are most appropriate if we want the maximal controllability [9, 10, 12, 8].

For pain relief, smoothness is not an issue, but the necessity to achieve 100% control is, so it is best to use the version of fuzzy logic that corresponds to the maximal controllability: with $\min(a, b)$ as "and" and $\min(a + b, 1)$ as "or".

Neural networks tune the rules. To utilize the knowledge described by the experience stored in the database, we apply a well-developed universal computer-based learning tool for extracting knowledge from data: *neural networks*, to train the fuzzy rule-based expert system.

4 Second stage: selecting the programs

4.1 How this is currently done

The new tool has access to up to eight contact points. It has the following possibilities:

- It is possible to choose which exactly points we want to target, and what polarity signals (+ or −) we are going to send to each of these points. This information is described by a assigning 0, −, or + to each contact point. For example, if we send a + signal to point No. 2, − signal to point No. 3, and nothing to all other points, then this combination of polarities is described by a sequence $00 + -0000$.
- We can also change the amplitude A, the frequency f, and the pulse width w of the signal sent to all the contact points.

The choice of all these parameters (polarities, amplitude, etc.) forms a *program.*

The program is usually chosen in the following manner:

- There is some preliminary knowledge that describes what exactly polarities and what frequencies we need to reach different pain locations. For example, if the pain is caused by moto-neurons, we need a frequency of ≈ 1 Hz; to target pain on other neurons, we need larger frequency ($\approx 10-20$ Hz), etc. We use this preliminary knowledge to generate the first (draft) programs.
- After that, we start experimenting with the patients. Namely, we start with the smallest possible amplitude that is, most probably, unfelt by the patient, and increase the amplitude until the patient starts feeling the effect. The patient must also indicates in which of the zones he has this feeling.
  - If some of these feelings are in the undesired zones, we must adjust some parameters of the program. There are some rules for that, but these rules do not describe all possible situations; so, if the situation is not covered by these rules, a trial-and-error approach is used.
  - If all the feeling are in the desired zones, we start increasing the amplitude until we get a level when the feeling becomes uncomfortable.

For a given program, these two thresholds are marked down, and in the future, amplitudes of using this program must be between these two values.

This methodology is based on the implicit assumption that if we send the same signal to the same patient twice, he will get the same feeling. This is not always true. The patient's reaction is somewhat uncertain, so he/she may get different feeling from the same program. To take this uncertainty into consideration, some practitioners, instead of a steady increase in amplitude, try different amplitudes in random order. As a result, we not only get the desired thresholds, but we also get an estimate for the accuracy of these thresholds.

Thresholds also change with time. For example, the experience of medical doctors shows that the initial values of the discomfort threshold are often simply caused by the unusual character of the feelings caused by the electric stimulation. As the patient gets accustomed to the stimulation signals, his dis-comfort threshold grows to the level of the objective threshold, so called motor threshold, which indicates the level at which the electric stimulation causes some undesired motor activity. It may be, therefore, reasonable to ignore the dis-comfort threshold and looks for motor threshold instead.

4.2 The problems

Experts' rules are often formulated in informal terms. As on Stage 1, the rules exist, but they are often formulated informally. It is desirable to formalize them and design a computer-based tool for selecting programs.

We cannot try all possible options. In the cases that are not covered by the rules, when we use trial-and-error method, there are too many different options, and simply trying them all is not possible. We need some intelligent methods of generating a few programs that are worth trying.

It is desirable to minimize the energy and thus, maximize the lifetime of an implanted energy source. It may be that a certain program achieves the desired pain relief, but in this program, we send signals to all the contact points, and the pulse width is high, so, as a result, this signal requires lots of energy and discharges the implanted battery too soon. In this case, it is desirable to check whether it is possible to decrease the energy of the signal (this, extending the battery lifetime) and still achieve the same pain relief.

4.3 Our approach

An expert system is needed. First (similarly to Stage 1), we design a fuzzy logic-based expert system incorporating the existing rules.

To make seacrh feasible, we need a simple model. Second, for the case when no rules are applicable, we must use a simple model that would ease the trial-and-error approach. This model must describe how the the effect E_α on each of (dozen or so) body locations α depends on the activation $A_1, \ldots, A_n$ of different contact points. How can we find such a model?

How can we measure the effect? The first problem that needs to be overcome is how to measure the effect. For that, we need to choose some unit measure. In principle, we have two different thresholds to serve as these units; however, as we have mentioned, the dis-comfort threshold is very subjective, so we would rather use an effect threshold as the desired unit. Then, if we apply a certain program with amplitude A, and the feeling threshold in a given zone is A_f, we take the ratio A/A_f as the effect of this program on this zone. The dis-comfort (or motor) threshold can be also expressed in these units.

Using a linear model. A natural idea is to start with a *linear* model in which E_α linearly depends on the amount of signals sent to different zones. There are two reasons for that:

- First, linear models are the simplest possible models, and in many areas of physics, engineering, etc., they form a reasonable first approximation.
- Second, we are talking about electromagnetic effects, and the equations that describe electromagnetic fields are linear. So, we hope that the resulting pain relief effects will also be well described by a linear formula.

Since it is known that signals of different polarity lead to different physiological effects, we must use different coefficients for positive and negative signals:

$$E_\alpha = \sum_{i=1}^{n} k_{\alpha i}^{\varepsilon_i} A_i,$$

where ε_i is the polarity ($+$ or $-$) of the signal sent to contact point number i. The linear model is a good first approximation, because the combination of two signals always covers exactly the same areas as one of these signals separately; however, this linearity needs to be thoroughly experimentally checked. For the linear model, we can describe our goals in precise mathematical terms: $\sum k_{\alpha i} A_i < 1$ for all zones that we do not want to affect (because there is no pain there), and $\sum k_{\alpha i} A_i < A_{\text{discomfort}}$ for all the zones. Ideally, we would like a program to cause pain relief in all the zones α where there is pain: $1 \le \sum k_{\alpha i} A_i$, but in reality, often, a program can only ease pain in *some* of these zones; so, if the best relief is impossible, we will at least need some relief. This resulting problem belongs to a class of so-called *linear programming* problems that can be solved by using the existing software.

We can borrow techniques from image processing. Another possibility is to use the *image processing* techniques, as developed, e.g., in astronomy. Stars are usually so far away that, in principle, their images should be viewed as points. However, due to atmospheric turbulence, these images blur. As a result, e.g., two distant starts are seen not as two points, but as a single mixed blur. There are lots of techniques that take these blurry images and find the smallest possible number of point objects that could cause the observed image, such as the CLEAN method and its modifications [5, 7]. In our case, we have a similar problem: each contact point affects several body zones. We can therefore use the (modified) CLEAN method to find the smallest possible number of point contacts that cover the desired set of zones.

Interval methods are useful. Due to subjective uncertainty, instead of the precise values of the coefficients $k_{\alpha i}$ and of the dis-comfort level, we get *intervals* of possible values. In this case, we use methods of *interval computations* (see, e.g., [2, 3] to describe not only the solution itself, but the *accuracy* of the resulting solution.

Interval computations also lead to an answer to the following related problem: when do we stop improving the program? If after a few iterations, the difference between the resulting effects is smaller than a patient can reliably distinguish, then, probably, no further improvement is possible.

What if we also know probabilities? If, in addition to the intervals of possible uncertainties, we know the probabilities of different uncertainties, then, we get a problem of optimization under the random noise. We can, therefore, use the existing *stochastic optimization* techniques to solve this problem.

What if a linear model is not adequate? When a linear model approximation is not sufficient, we must use quadratic models.

If no model is available, we need an intelligent method of choosing an appropriate program. Currently, there exists an automated tool (developed by Dr. North) that works for the case of 4 contact points. In this case, we have $3^4 = 81$ possible combinations of 3 possible signals 0, +, and $-$. So, this tool enables to automatically try all 81 of them and ask the patient to indicate which zones are affected by the corresponding combination. Then, the desired combination is selected. For 8 contact points, we already have $3^8 = 6,561$ combinations. This is too much to check (and 8 contact points is definitely not the limit). Therefore, we need an intelligent method of choosing the appropriate combination.

For designing such a method, we use the experience of the existing computer techniques for constrained optimization. These techniques enable us to find a sequence of values that leads to the maximum of a given objective function under certain constraints without the necessity of trying all possible combinations of parameters. These techniques usually require that the objective function be given as a program. In our case, the "objective function" is a feedback from the patient. So, we can use the same methods in which every time the algorithm asks for an objective function we simply test this particular combination on the patient. (In particular, we can use genetic algorithms or other techniques.)

5 Third stage: combining the programs

Modern engineering tools enable not only to run *individual* programs, but also to run *combinations* of programs, so that if we cannot find a single program to ease all the pain, a combination of several programs each easing a pain in a certain area will hopefully ease all the pain.

5.1 How this is currently done

After the initial programs are selected, we ask a user to sort them according to their ability to relieve the pain. Then, usually, we select a combination in the following manner:

- First, we take a program that covers most of the zones that we want to cover. If this program covers all, we are done. If not, we need more program combined:
- If the first program does not cover all the pain zones, we select the next program to cover most of the un-covered zones,
- etc.

5.2 The problems

The resulting combination may not be the best. There is no guarantee that the resulting combination is indeed the best. From the computer science viewpoint, what we are doing is the so-called *greedy algorithm* (see, e.g., [1]), where we take the first element to cover the most, the second to cover the most of un-covered, etc. It is known that while in some situations, greedy algorithms lead to the optimal solutions, in many situations, other algorithms are better: it may be better, e.g., to combine two programs each of which completely eases the pain in each of the two pain zones rather than experiment with a single program that covers both zones but not eases the pain that well. Ideally, it is desirable to try all combinations in a program. However, realistically, we have 24 possible programs in the new

Quest tool, which make $2^{24} \approx 16$ million possible combinations. There is no way that we can try them all. So we need some intelligent techniques for trying some of them.

It is desirable to minimize energy. Some combinations may be pretty efficient but too energy consuming. So, we may want to try to eliminate some components in hope of achieving the same combination effect with smaller energy (and thus, with a longer battery lifetime).

5.3 Our approach

Optimization method. When programs are selected, the problem of choosing an appropriate combination becomes the program of choosing a subset of the set of these programs. An arbitrary subset of the set of 24 programs can be described by a sequence of 24 0's and 1's: 0 on i-th place indicating that i-th program is not included in the set, 1 indicating that the i-th program is included in the set. Among all optimization methods known in mathematics, there is one class of methods that is specifically designed for optimization problems in which an argument is a binary sequence (i.e., a sequence of 0's and 1's): this is the class of genetic algorithms (that simulate evolution in nature). Therefore, we are planning to use genetic algorithms to find the best combination (e.g., a combination that achieves the desired pain relief with the smallest possible number of programs combined).

6 Future plans

Short-term plans. Our short-term plans are to experimentally test our ideas on real patients, fine-tune them if necessary, and design a user-friendly expert system implementing these ideas.

Medium-term plans. In the current pain-relief procedure, there is one additional problem that we did not take into consideration in our expert system design: Namely, after being placed within the patient, the electrodes may spontaneously move. As a result, the same signals are now applied to different points on the spine, and therefore, not easing the pain any longer. Our medium-term future plans are to solve this problem.

- It is desirable to figure out, by looking at the resulting new pain effect map, where exactly this move has occured, and how we can reprogram the device to achieve the pain relief. Again, there are rules for that, but these rules need to be formalized and incorporated into an expert system.
- We want the placement of electrodes to be correctable in the sense that if we cannot reprogram them, we will be able to move them some and still achieve the desired pain relief. There are some rules for that too: e.g., it is relatively easy to move the electrodes down, but it requires a serious surgery to move them up the spine. These rules need to be formalized and taken into consideration.

Long-term plans. The ultimate goal of this research is to design a system that will do the following:

In the planning stage, the patient specifies the degree and exact location of the pain by using a 3D image in the Interactive Virtual Environment (VE). This information will be fed into an Artificial Intelligent System that will display the best location for the sending device to be located in relation to the spinal cord.

To accomplish the implementation stage, an inventive approach will be taken to integrate a useful haptic device into the VE. The VE will be created from 3D models that will represent the actual characteristics of the human body (i.e., spinal architecture) as well as the hardware used in Spinal Cord Simulation. The system will allow the doctors to visualize, by means of a color scheme, which parts of the body are to be affected by the placement of a sending device. The affected area will be updated in real time as the doctor moves the device within spinal cord. The color scheme will represent the range and degree of coverage that each area is capable of receiving from the sending unit. The input that will determine how the colors are presented on the models will come from an Artificial Intelligence (AI) system.

This haptic/3D visualization approach will aid the physicians in placing the sending units and in the post implementation period maintenance by optimizing direction and flow characteristics.

Possible application of SCS to other medical problems. The success of SCS as a method of treating chronic pain has led to the successful suggestions of using the electrical stimulation of the spinal cord to treat other neuron-related diseases such as motor system malfunctions (spasticity, dystonia, tremor, etc.), ischemia and ischemic pain of the heart and blood vessels, etc. The corresponding research is currently at different stages of investigation.

Acknowledgments

This research was partially supported by the U.S. Army Research Office, via the Advanced Distributed Simulation Research Consortium, and by the National Science Foundation (NSF), via the funding for the Center for Computational Science and Advanced Computer Simulation. V. Kreinovich was also partially supported by NASA under cooperative agreement NCCW-0089, by NSF grants No. DUE-9750858 and EEC-9322370, and by the Future Aerospace Science and Technology Program (FAST) Center for Structural Integrity of Aerospace Systems, effort sponsored by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF, under grant number F49620-95-1-0518.

We are very thankful to our colleagues for valuable discussions. We are especially thankful:

- to our *medical* colleagues Giancarlo Barolat (Thomas Jefferson University, Philadelphia, PA), Claudio A. Feler (Semmes Murphy Clinic, Memphis, TN), Jay D. Law (Colorado Neurological Institute, Denver, CO), and Mark Y. Yland (Huntington Center for Pain Treatment, Huntington, NY),
- to our *computer science* colleagues Aon Tejani (University of Houston-Downtown) and Homero Vladimir Rios Figueroa (National Laboratory of Informatics, Veracruz, Mexico).
- and, last but not the least, to medical *engineers* from the Quest Medical Inc. (Allen, TX), especially to Rick Daignault,

References

[1] Th. H. Cormen, Ch. L. Leiserson, and R. L. Rivest, *Introduction to algorithms*, MIT Press, Cambridge, MA, 1990.

[2] R. B. Kearfott, *Rigorous global search: continuous problems*, Kluwer, Dordrecht, 1996.

[3] R. B. Kearfott and V. Kreinovich (eds.), *Applications of Interval Computations*, Kluwer, Dordrecht, 1996.

[4] G. Klir and B. Yuan, *Fuzzy sets and fuzzy logic: theory and applications*, Prentice Hall, Upper Saddle River, NJ, 1995.

[5] O. M. Kosheleva, V. Kreinovich, and B. S. Minchenko, "A modification of the CLEAN algorithm of radioimage reconstruction." *Proceedings of the XYII National Radioastronomical Conference*, Erevan, 1985, p. 123 (in Russian).

[6] B. Kosko, *Fuzzy engineering*, Prentice Hall, Upper Saddle River, NJ, 1997.

[7] V. Kreinovich, "A modification of the generalized CLEAN method", *Notices of the American Mathematical Society*, 1979, Vol. 26, No. 5, p. A-438, Publ. No. 79T–C58.

[8] V. Kreinovich, H. T. Nguyen, and E. A. Walker, "Maximum entropy (MaxEnt) method in expert systems and intelligent control: new possibilities and limitations", In: K. Hanson and R. Silver, Eds., *Maximum Entropy and Bayesian Methods, Santa Fe, New Mexico, 1995*, Kluwer Academic Publishers, Dordrecht, Boston, 1996, pp. 93–100.

[9] V. Kreinovich, C. Quintana, and R. Lea, "What procedure to choose while designing a fuzzy control? Towards mathematical foundations of fuzzy control", *Working Notes of the 1st International Workshop on Industrial Applications of Fuzzy Control and Intelligent Systems*, College Station, TX, 1991, pp. 123–130.

[10] V. Kreinovich, C. Quintana, R. Lea, O. Fuentes, A. Lokshin, S. Kumar, I. Boricheva, and L. Reznik, "What non-linearity to choose? Mathematical foundations of fuzzy control", *Proceedings of the 1992 International Conference on Fuzzy Systems and Intelligent Control*, Louisville, KY, 1992, pp. 349–412.

[11] H. T. Nguyen and E. A. Walker, *A first course in fuzzy logic*, CRC Press, Boca Raton, FL, 1997.

[12] M. H. Smith and V. Kreinovich, "Optimal strategy of switching reasoning methods in fuzzy control", Chapter 6 in H. T. Nguyen, M. Sugeno, R. Tong, and R. Yager (eds.), *Theoretical aspects of fuzzy control*, J. Wiley, N.Y., 1995, pp. 117–146.