Signal processing via sampled-data control theory

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Impact Objectives

- Undertake research aimed at optimally controlling or reconstructing signals in regard to analogue characteristics
- Develop a new method enabling recovery of lost intersample high-frequency signals optimally

Re-thinking signal processing

*The loss of digital data between sampling points has a considerable impact on the quality of sound recordings and images. Researchers, led by **Professor Yutaka Yamamoto**, Professor Emeritus at **Kyoto University**, have developed a way to recover data at high frequencies. They believe this could fundamentally change what is at the core of modern digital technologies*

Digital sounds and images are used everywhere today, and they are all generated originally by analogue signals. On the other hand, in digital signal processing, the storage or transmission of digital data, such as music, videos or image files, necessitates converting such analogue signals into digital signals via sampling. When these data are sampled, the values from the discrete, sampled points are kept while the information between the sampled points is lost. Various techniques have been developed over the years to recover this lost data, but the results remain incomplete.

Professor Yutaka Yamamoto, Professor Emeritus at Kyoto University, has dedicated his career to understanding more about this significant issue. He has focused on improving how we can recover or reconstruct the original analogue data. Yamamoto explains that conventional sampled-data control theory generally ignored intersample signals. 'This means that when a controller is designed based on the sample-point model, undesirable intersample behaviour occurs,' he outlines.

DIGITAL SIGNAL PROCESSING

On the side of digital signal processing, Claude Shannon published a seminal paper in 1949 tackling this issue with signal reconstruction using the sampling theorem. He highlighted that the original analogue information from sampled data can be recovered provided the original analogue signal remains band-limited below the Nyquist frequency. This frequency was named after Harry Nyquist, an electronics engineer and inventor, and is half the sampling rate of the discrete signal processing system. The work by Shannon resulted in the establishment of the Shannon Paradigm, which has become a basis for communication and digital processing that is now used across the world.

A NEW APPROACH

The band-limiting hypothesis, however, poses a strong limitation, resulting in loss of details and high-frequency signals. Yamamoto stresses that this limitation represented by the Shannon Paradigm was imposed only as a sufficient condition rather than the necessary condition it has often been treated as by much of the signal processing community. 'The widely held belief that frequencies over the Nyquist frequency cannot be processed has imposed serious limitations due to the lack of high frequencies allowed in applications such as music, where this leads to ringing and metallic sounds in the recordings,' he explains.

In the 1990's Yamamoto introduced a new way to look at sampled-data control systems known as the lifting method. What he proposed offered a major advantage over the existing approaches. 'The new approach makes it possible to optimally recover the

Custom-made audio DA converter recovering up to 170 kHz

A superresolution result processed from the downsampled degraded image

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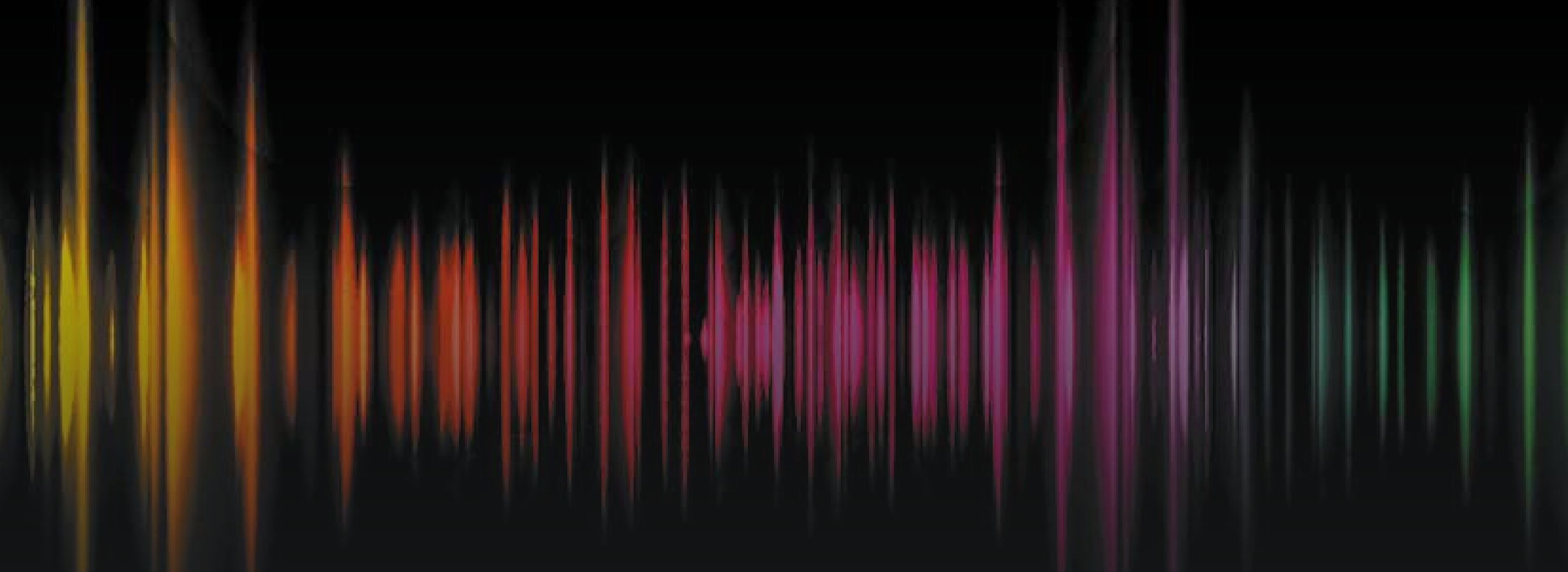

intersample signals, which not only resolves the serious problem in sampled-data control theory, but is also applicable to the digital signal reconstruction problem,' highlights Yamamoto. At the heart of this is being able to look at problems in a simpler way.

BEYOND THE SHANNON PARADIGM

Along with his colleagues Professor Masaaki Nagahara from the University of Kitakyushu, and Professor Pramod Khargonekar from the University of Florida, Yamamoto introduced the above new sampled-data method into designing a digital filter in signal reconstruction and also sample-rate converters. Their idea was that they could optimise the analogue-domain performance across all ranges of frequency. 'As a result of taking the analogue performance into account, the designed converter has yielded much more satisfactory time and frequency responses,' he explains.

Their focus was to leverage the sampled-data control theory to identify a new way to reconstruct signals. 'We formulate the signal reconstruction problem in terms of an analogue performance optimisation problem using a stable discrete-time filter,' outlines Yamamoto. In this study, the team investigated and identified how optimal solutions could be delivered. They also compared alternative methods in detail and then offered possible applications for reconstructing both sounds and images.

Yamamoto says that they based these steps on modern sampled-data control theory, which researchers, including himself, have progressed since the 1990's. 'The fundamental accomplishment of modern sampled-data control theory is that it can give us a discrete-time controller (or filter) that optimises the closed-loop performance with intersample behaviour taken into account,' he explains. This is the basis from which they were then able to use to reconstruct the original analogue signals from sampled-data. 'This setting gives us an optimal platform to reconstruct the original analogue signals from sampled-data under the scenario that the original signal is not band-limited below the Nyquist frequency.'

The design method consists of the following steps. Firstly, an analogue filter is introduced to model the basic signal generator. Next, the signal reconstruction is formulated as a sampled-data control design problem. Then a controller (a digital filter) is designed to reconstruct the original analogue signal. 'The advantage here is that we can formulate an overall error system, and be able to have control over all frequencies including both gain and phase errors, not merely the gain characteristics often observed in many filter designs,' observes Yamamoto. Through these extensive collaborative investigations, they were able to identify a new digital signal processing framework.

REAL-WORLD IMPACT

Yamamoto explains that their findings have wide applications and many benefits. 'Our methodology applies to a variety of theoretical and application problems in digital signal processing.' He is hopeful that this approach can now be applied more broadly to help address the challenges in reconstructing the original analogue signal.

This work further led Yamamoto, Nagahara and his daughter Dr Kaoru Yamamoto, who is an Associate Professor at Kyushu University, to explore the signal reconstruction problem in a more general context. This approach enabled them to deal with non-stationary signals that appear in generalised settings, and is applicable to signals in the time-frequency domain such as wavelets. These investigations were presented, for example, at the 2017 IEEE 56th Conference on Decision and Control (CDC) in Australia.

There are a number of patents that Yamamoto and his colleagues have in place now. These include a method and apparatus for removing image noise, as well as a method for designing an audio signal processing system for a hearing aid. The SANYO (now Panasonic) Corporation have based their very successful LSIs sound-processing chips on patents developed by Yamamoto's theory and patents.

> *'The new approach makes it possible to optimally recover the intersample signals, which not only resolves the serious problem in sampled-data control theory, but is also applicable to digital signal reconstruction problem'*

Yamamoto's approach has challenged existing methodology in the field of control and signal processing. Demonstrating the effectiveness of his results to both his peers and the general public is an obstacle that he must overcome. This new method has led to decisive results in digital signal processing and this, in turn, has led to unexpected new progress in digital control of hypertracking and hyperrejection. Looking forward, Yamamoto believes there is still much work to be done to elicit better recovery of lost signal data in control, and this issue is long forgotten. 'We hope to open up new opportunities in digital control in that it will greatly remove the limitation of the Shannon paradigm that confines frequencies below the Nyquist frequency,' he concludes.

Reclaiming sample data loss

***Professor Yutaka Yamamoto**, Professor Emeritus at **Kyoto University**, talks in more detail about his ground-breaking work on signal processing via sampled-data control theory, and offers some personal observations on this journey*

Professor Yutaka Yamamoto

Dr Kaoru Yamamoto

Professor Masaaki Nagahara

Professor Pramod P Khargonekar

You have an extensive career in control theory. Can you talk a little about your own research background?

I am a control theorist and have been studying systems and control theory since 1974. I studied modelling of infinite-dimensional systems during and after my PhD at the University of Florida under the guidance of the late Professor RE Kalman – renowned for the invention of the Kalman filter. Later, I became more interested in how sampled-data systems can be naturally formulated or modelled, because I was aware that there was a serious problem in accommodating their intersample behaviour into models. Classical treatments always fail to include the intersample behaviour into the sampled-data control model, and this often creates a serious problem in their design. This led me to the idea of lifting, which revolutionised the theory of sampled-data control systems. The new theory enabled us to optimally control the analogue behaviour of sampled-data control systems, including their intersample behaviour – not merely their sample point performance. This success led me to wonder what would happen if we applied this new methodology to digital signal recovery, as I had always been wondering about the justification of the sharp frequency truncation characteristic of modern DA converters employed in digital sound processing, as used in CDs, relying on the Shannon theory. So, I formulated the digital signal reconstruction problem in terms of modern sampled-data control theory. The result demonstrated a clear advantage over conventional DA converter designs based on the Shannon paradigm.

You are working on an idea that you can apply the sampled-data control paradigm beyond the Shannon paradigm. Can you explain what this means in layperson terms?

Sampling means that values are picked at discrete, usually uniformly spaced points called sampling points. As a result, we lose the unsampled data. There are many ways to fill in the gaps or missing data. Shannon established a way of doing this by assuming that these missing data vary as slowly as possible. This is one good way of filling the gaps but tends to lack detailed information. For example, the high-frequency notes in sounds and finer detail in images. The present method allows us to augment or supplement this missing information based on a different and more natural signal model. For example, musical instruments can have their own frequency characteristics and they can be employed as natural signal generator models. The present method allows us to include such models in the reconstruction system and makes it possible to reconstruct the lost information in an optimal way. This is an outcome of modern sampled-data control theory.

What are you hoping to achieve through this research?

Sampling loses information between sampling points. It has been considered impossible to fully recover or reconstruct such intersampling information. Shannon's sampling theory sets a hard limit in reconstructing original analogue signals. However, it is possible to optimally (but not perfectly) recover such intersample information via modern sampled-data control theory with a suitable analogue signal generator model. Using this technique, we can extend the frequency range of musical signals much higher than the Nyquist frequency – the conventional limit. The same technique can also be effectively applied to images. This is called superresolution and gives a much finer resolution than that expected from the Shannon theory. We intend to use modern sampled-data control theory to optimally augment intersample information lost by sampling.

Who will benefit from your learnings?

Our work will benefit virtually everyone who listens to music, watches videos or views images via digital media once this technology is adopted. This has already occurred on a smaller scale through the LSI chips that the SANYO corporation has produced; they have sold more than 75 million LSI chips. Ultimately, this will benefit anyone who makes use of digital image or sound processing, and any apparatus that uses digital processing. ●

Project Insights

COLLABORATORS

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BIO

Professor Yutaka Yamamoto is a Professor Emeritus of Kyoto University. He was President of the IEEE Control Systems Society, President of ISCIE, Japan. Yamamoto is a recipient of the GS Axelby outstanding paper award, and Transition to Practice Award of the IEEE CSS, Tateishi Prize, Commendation of Ministry of Science and Culture. He is a life fellow of the IEEE, also a fellow of the IFAC and SICE, Japan.