Jämsä-Jounela, Sirkka-Liisa

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Review

Current status and future trends in the automation of mineral and metal processing

S.-L. Jämsä-Jounela*

Department of Chemical Technology, Aalto University, Kemistintie 1, FIN-02150 Espoo, Finland

Abstract: A review of the current status and future trends in the automation and control of mineral and metal processing is presented. An evaluation of publications on IFAC MMM events during the last 20 years shows some trends in the application of a number of process control methods in the MM industry. Classical control has seen an extraordinarily wide application, but its inability to solve all the application problems of interest has led to further developments in control system methodologies and theory. One aim of this paper is to review the success of the translation of theoretically based developments into practice. Finally, the importance of information technology for the MM industry and process automation is highlighted and discussed.

Keywords: Process control; Industrial application; Automation; State-of-the-art; Mineral and metal processing

1. Introduction

Industrial automation is undergoing a change that is more rapid than at any other time in its history. Where earlier systems mainly followed process developments, new methods are now revolutionising the entire field of process management. The fields of mineral and metal processing continue to provide challenges in the application of process control at every level of the automation hierarchy, enterprise optimisation and systems integration.

In the early 1960s, the emergence of the maximum optimal principle, dynamic programming, Kalman filter and state space description marked the birth of modern control theory. Since then, more attention has been focused on MIMO control theory. During the last three decades, modern control methods have been improved and applied in a range of industrial processes. Since 1980s the fields of non-linear control systems, H_∞ control, adaptive control, discrete event systems and AI control have received attention and applications have been developed. Although there has been major progress in the control theory, it still has a long way to go to industrial control as reported by Chu, Su, Gao, and Wu, 1998.

A review of the current status and future trends in the automation and control of mineral and metal processing is presented in this paper. An evaluation of publications on IFAC MMM events during the last 20 years shows some trends in the application of a number of process control methods in the MM industry. One aim of this paper is to review the success of the translation of theoretically based developments into practice. To illustrate the relationships between theory and practice, the most successful industrial applications over the years will be described in more detail according to the kind of processes. The examples have primarily been selected from contributions to the IFAC MMM events.

2. Instrumentation and fieldbuses

Instrumentation is an area that is currently undergoing rapid changes as field communications move from analog to digital protocols. The major advantages of smart instruments are: remote calibration and diagnostics, self-monitoring and remote configuration. Remote operations permit an easier and more flexible configuration, thus reducing start-up costs of automation systems. Self-monitoring enables predictive maintenance, which makes it possible to schedule service operations precisely on time. This helps to avoid shutdowns due to the malfunctioning of instruments and needless service operations.

The type of communication protocol is one of the major factors categorising modern field devices. Classical analog field instruments use a 4–20 mA current signal for one-way communication. Digital microprocessor-based field devices have made bi-directional communication possible.

At the time when the number of digital field devices was increasing, most of the factories used an old 4–20 mA analog signal as a communication media. This led to the HART protocol.

HART is an acronym for "Highway Addressable Remote Transducer". The HART communication is accomplished by superimposing the digital signals on the top of an analog 4–20 mA signal. This enables two-way communication and makes it possible for additional information to be transferred to/from a smart field instrument (Anon 1, 2000).

Fieldbus is an all-digital, high-performance, multi-drop communications protocol, which is used to link isolated field devices. Fieldbus requires new transmission technology for digital communication, such as IEC 1158-2 (Anon 2, 1999). Fieldbus is a communication media that enables two-way communication between field devices and an automation system.

Currently, there are several fieldbus standards available on the market, each generated to meet a number of specific needs. Some fieldbuses focus on the control of analog data, some on digital information, while others have speed as their major feature. Process industries have three main possibilities of using smart instruments, the Hart Protocol, two competing digital fieldbuses of Profibus PA or Foundation Fieldbus (FF), or not to use smart instruments at all.

Profibus is a leader with respect to the number of applications and devices on the market in Europe. The strength of the initially American FF compared to Profibus PA is that the FF supports the distribution of control actions in the field.

The number of smart instruments is gradually increasing. The users are unaware of which of the three possibilities is the right one for their applications. The benefits gained are also under discussion. One problem is the increased power consumption because faster and more powerful microprocessors are being used. This must be taken into account when "intrinsically safe" certification is required. Most of the digital fieldbuses have been installed in the new factories. Until now, the users have had to compromise, partly due to the fieldbus connectivity restrictions set by the automation systems, and partly due to the properties of fieldbus as such.

3. Automation systems

The ever-increasing variety and complexity of the automation systems make it impossible to even attempt to present an exhaustive survey of their current status in a short paper. The changes induced by fieldbus are expected to result in very profound changes in the hardware and operating software. In the DCS/PLC debate that has raged over the past decade, the vendors of these systems have mainly seen their future roles as software suppliers and platform integrators with the focus on applications that differentiate them through the value-added to the end users. Openness has become an essential part of automation. New NT-based systems are now embedded with a mill's information tools. Where earlier systems mainly followed process developments, the new methods are now revolutionising the entire process management.

4. Industrial applications of the different control methods

The following survey attempts to comment on developments in the field of process control on the basis of application-oriented papers from selected IFAC MMM events during 1980–2000. The following events were taken into account:

- IFAC MMM Symposium, 1980, Montreal, Canada.
- IFAC MMM Symposium, 1983, Espoo, Finland.
- IFAC MMM Symposium, 1986, Tokyo, Japan.
- IFAC MMM Symposium, 1989, Buenos Aires, Argentina.
- IFAC Workshop on Expert Systems in Mineral and Metal Processing, 1991, Espoo, Finland.
- IFAC MMM Symposium, 1992, Beijing, China.
- IFAC MMM Symposium, 1995, Sun City, South Africa.
- IFAC Workshop on Automation in the Steel Industry, 1997, Kyongju, Korea.
- IFAC MMM Symposium, 1998, Cologne, Germany.
- IFAC Workshop on Future trends in Automation in Mineral and Metal Processing, 2000, Finland.

Only those contributions which take into account control or monitoring applications with pilot or industrial mineral and metal processing full-scale processes are considered. Simulations were not included. The applications were classified on the basis of the methods listed in Table 1.

The summary of the literature study is presented in Table 2 and the results are discussed in more detail in the following chapters.

Table 1
Process control and monitoring methods

110	P, PI, PID
120	Model-based control
	Feedforward
	Model predictive control
130	Multivariable control
140	Adaptive control
150	AI-control
	Knowledge-based expert system
	Fuzzy logic
	Neural networks
	Genetic algorithms
160	Fault diagnosis and process monitoring
170	Quality monitoring

4.1. *Kind of processes and control methods*

Successful industrial applications of the control methods have been reported worldwide. The number of applications published over the years in the IFAC MMM events is shown in Fig. 1. It shows that the total number of reported industrial control and monitoring implementations is 148, the average number per event being 14.

Fig. 2 shows the distribution of the different methods according to the kind of process. The greatest number of applications have been made in the field of mineral processing, blast furnaces and furnaces, hot rolling and oxygen steel making and continuous casting, in this order. Fewer investigations have been carried out on control applications in cold rolling, hydrometallurgy and electrorefining. The same trend can also be seen from the distribution of application distributions per event in Fig. 1.

Fig. 3 shows the distribution of implementations according to the kind of control or supervision methods during the period 1980–2000.

Classical control can be seen to have found extraordinarily wide applications during the first three events. The number of classical control applications has decreased over the years, indicating that this technique is mature and is in everyday use at many plants. It is well known that a vast majority of industrial control loops (more than 90%) still rely on various forms of PID controllers.

The inability of classical control methods to solve all the application problems of interest has led to further developments in control system methodologies and theory. One aim of this paper is to review the success of the translation of theoretically based developments into practice.

AI methods can be seen in most industrial applications since 1991 compared to other methods. The applications have mainly considered three AI methods: expert systems, neural networks and fuzzy control. They are used in nearly 40% of all applications reviewed, and therefore represent the most important methods applied in the control and monitoring of MM processes. It has been widely reported that AI methods are ideal candidates especially for MM processes. The importance of artificial intelligence techniques in real-time process control is emphasised in the articles, and the MM processes are reported to benefit from the applications of AI techniques.

During recent years the exploitation of fault diagnosis and process and quality monitoring indicates that control engineering is expanding to include tasks other than control. This represents a potential contribution to the automation of the MM industry in the future. In the 1998 Symposium, these methods were used in 46% of all the applications considered, and in this workshop, in 30% of the applications.

Modern developments in process control and monitoring theory continue to find applications in the metal-processing industry. To illustrate the relationship between theory and practice, the most successful industrial applications over the years will be described in more detail below according to the kind of process, and compared to the general trend presented above. The examples have mainly been selected from contributions to the IFAC MMM events listed above.

4.1.1. *Mineral processing*

Based on the survey, investigations on industrial control applications in the mineral processing field were mainly focused on grinding and flotation unit processes. In recent years new application areas have also been reported, such as a pressure filter and a rotary drier.

Table 3 shows that multivariable control and AI are the methods mostly applied in mineral processing.

In the Symposium in 1980, Hulbert, Koudstaal, Braae, and Gossman (1980) reported multivariable control of the grinding process. The system can control variables related to circulating load, classification conditions, and the size of the product. This was followed by the Finnish application presented by Jämsä, Melama, and Penttinen (1983). These multivariable control applications based on the Inverse Nyquist Array (INA) method are still running in the South African concentrators. Although many industrial applications have shown that the decoupling control strategies are very effective and applicable, the Finnish product was withdrawn from the market due to difficulties in understanding, tuning and using the control system by the plant operators.

The power of model-based control for mineral processing operations was discussed in the next MMM symposium in Beijing by Herbst and Pate (1987). Three examples of model-based control strategies for mineral processing operations were presented. One was an open

Table 2
Industrial control applications published in the IFAC MMM events during the period 1980–2000

			Title	Authors	Year
Classical control methods	Mineral processing	Grinding	Process control of the ball mill grinding and classification	Zhao Weiguang	1992
			Hierarchical control of a grinding-classification circuit	D. Sauter, M. Auburn, and J. Ragot	1983
			Computer control of lead/zinc concentrator crushing plant operations of Mount ISA Mines Limited	E.V. Manlapig and R.M.S. Watsford	1983
			Modelling and computer control of a ball mill unit	P. Heitzmann, C. Humbert, and J. Ragot	1980
		Flotation	The use of concentrate diverters in flotation control	D.J. McKee, C.A. Dawes, and C.J. Seaborn	1983
			The implementation of process computer control at the snow lake concentrator	L. Chutskoff, K.C. Carriere, L. Betteridge and B. Dishaw	1980
	Hydrometallurgy		Experience on SX/EW pilot plant automation	L.G. Bergh	2000
	Furnaces		Control method for rotary kiln with a hard accessible quality parameter	P. Bak, M. Piwowarski, and Z. Sokalski	1980
	Hot rolling		Minimal tension roll speed control system for hot rolling mills	I.B. Junger	1995
			Development of PC mill control system	Y. Hayama, J. Nishizaki, T. Kajiwara, and M. Abe	1986
			Roller mill as a control object	J. Saito, M. Hosono, K. Shibuya, and Y. Okano	1983
			Design requirements for a hot strip mill process computer system	C. Whitfield and H. Baltussen	1980
			Unmanned slab and coil yard system for hot strip mill	S. Fujii, H. Sasao, E. Makabe, M. Iwamoto, S. Ohtaka, and M. Yoshino	1980
	Cold rolling		Advanced thickness gauge control system for tandem cold mill	Y. Naitoh, K. Kikuchi, T. Washida, T. Nakada, E. Susuki, and K. Tani	1989
Model based and model predictive control	Mineral processing	Grinding	Report on actual benefits arising from the application of expert control systems in industrial semi-autogenous grinding circuits	J.A. Herbst, L.B. Hales, and W.T. Pate	1989
		Flotation	An implementation of generalized predictive control in a flotation plant	M. Suichies, D. Leroux, C. Dechert, and A. Trusiak	1998
			The power of model based control for mineral processing operations	J.A. Herbst and W.T. Pate	1986
	Furnaces		Implementation of predective controller for thermal treatment processes	C. Lazar, E. Poli, and B. Mustata	1998
			Heat control system for tube-making by the extrusion process	Keizo Watsuji and Osamu Sugiyama	1997
			On the control of silicon ratio in ferrosilicon production	Helgi Thor Ingason and Gudmundur R. Jonsson	1997
			Predictive control applications for a thermal treatment process	Corneliu Lazar, Bogdan Mustata, and Ioan Nilca	1997
			Optimal usage of coking plant and blast furnace gases in an integrated steel work	P. Uronen	1989
			Development and application of observers based on complex mathematical models for hot strip mill reheat furnaces	D. Garcia, J. Prieto, A. Diez, F. Obeso, and J. Fernandez	1989

			A multiobjective optimization approach to a thremal designing problem of a continous-type electric furnance	K. Ito, T. Mukai, H. Yokohata, and Y. Sato	1986
			Computer control system for reheating furnace	Y. Wakamiya, M. Tsuruda, and T. Yamamoto	1986
			Identification and prediction of temperature difference across blant furnance bottom by AR model for control of tapping operation	K. Asano, M. Kondo, and T. Sawada	1986
			On-line computer control of straight grate indurators	R.C. Corson	1980
	Hot rolling		Revamp of the controller for the ROT-cooling at SSAB Tunnplåt AB:s Hot-strip-mill in Borlänge	M. Thurgren and P. Sixtensson	2000
			Application of temperature control system to a new hot strip finishing mill	Y. Tonami, K. Sekiguchi, M. Tsugeno, T. Takesako, C.R. Chen, C.H. Wen, and C.J. Tsai	1998
			Improved rolling-mill automation by means of advanced control techniques and process models	H. Frank, R. Pichler, M. Schoisswohl, and W. Staufer	1998
			Hot strip mill tension-looper control based on decentralization and coordination	K. Asano, K. Yamamoto, T. Kawase, and N. Nomura	1998
			An application of advanced control theory on shape control for thin strip rolling	K. Togai	1986
			Hot strip width control by computer	S. Bagnasco, F. Belgrano, G. Caluzzi, R. Galanti, and F. Manzo	1980
	Cold rolling		Modelling and optimisation for 20 high cold rolling mill	J. Heidepriem, R. Werners, and A. Schneider	1998
			Optimisation control of Sendzimir mill	T. Kawaguchi, T. Yamada, K. Katayama, and K. Kashiba	1980
Multivariable control	Mineral processing	Grinding	Control of a milling circuit to balance mills operation in parallel	D.G. Hulbert	1986
			Experiences in control system design of phosphate ore grinding in Siilinjarvi concentrator	S.-L. Jämsä and J. Aaltonen	1986
			Implementation of computer control on the milling circuit of the Buffelsfontein Gold Mining Company Limited	K.C. Garner, O.G. Pauw, and P.C. van Aswegen	1983
			The application of a microprocessor-based multivariable controller to a gold milling circuit	G.I. Grossman and A. Buncombe	1983
			Design and experimental evaluation of a multivariable grinding circuit control system	S.-L. Jämsä, H.Melama, and J.Penttinen	1983
			A linear-quadratic-Gaussian control algorithm for sulphide ore grinding	R. Ylinen, T. Iivarinen, and A. J. Niemi	1983
			Multivariable control of an industrial grinding circuit	D.G. Hulbert, J. Koudstaal, M. Braae, and G.I. Gossman	1980
		Flotation	Level control of cascade coupled flotation tanks	B. Stenlund and A. Medvedev	2000
			Multivariable control and pulp levels in flotation circuits	D.G. Hulbert	1995
			Experiences with optimal control in a chalcopyrite flotation circuit	I. Kaggerud	1983
			A new approach to analyzing 'Conventional' INA milling circuit controllers	I.K. Craig and V.P. Babarovich-Hansen	1995

Table 2 (continued)

			Title	Authors	Year
	Furnaces		Advanced kiln control system based on modern control theory	Y. Gakuhari, H. Tasai, and N. Yoshioka	1986
	Hot rolling		Observer-based multivariable control of rolling mills	I. Hoshino and H. Kimura	1998
			Optimal control system for hot strip finishing mill	M. Okada, K. Murayama, A. Urano, Y. Iwasaki, A. Kawano, and H. Shiomi	1997
Adaptive control		Grinding	Adaptive optimal control in ore grinding	Su Zhen	1992
			A Sequential suboptimal control strategy suitable for mineral processing plants	R.G. Gonzalez and U.G. Larenas	1986
		Conditioning	Application of a new generic optimal controller structure for raw material blending	Cs. Banyasz, L. Keviczky, and I. Vajk	1995
		Flotation	Identification and gain-scheduled control of a pilot flotation column	A. Desbiens, R. Del Villar, and M. Milot	1998
			The Pyhäsalmi concentrator—13 yr of computer control	J. Miettunen	1983
			Experiments with self-tuning control of flotation	A. Hammoude and H.W. Smith	1980
			Applications of adaptive control techniques to mineral processes	P. Massacci, G. Patrizi, and M. Recinella	1995
	Electrorefining		Adaptive control of alumina reduction cells with pointfeeders	J. Aalbu	1986
	Furnaces		Adaptive control for systems with time-delay	R. Mantz, E. Tacconi, and J. Carasi	1989
			A self-tuning multivariable predictor and its application to the control of sinter quality	E. Rose and P.P. Kanjilal	1986
			Optimal and adaptive control of strip temperature for a heating furnace in CAPL	N. Yoshitani	1986
	Ox. steelmaking and cont. casting		Feedforward control of gas recovery system for oxygen converters	L. Xin, M. Eng, and B. Eng	1989
			The automatic mould level control for a continuous casting process. Practical implementation of different control algorithms	J. Paiuk, A. Zanini, M. Remorino, and O. Frola	1989
			A program system for supervision of plants in steel industry	W. Heukeroth and J. Heidepriem	1986
			New automation and control technolgy of slab caster	H. Kato and M. Yamasita	1986
			Application of auto-tuning PI controller based on the ultimate sensitivity method to a flow control system	T. Tottori and N. Funabiki	1986
			Automatic control of casting speed in ingot casting	T. Shiraiwa, Y. Sakamoto, S. Kobayashi, S. Anezaki, H. Kato, and A. Kuwabara	1980
	Hot rolling		Adaptive control of metallurgical processes: principles and applications	N.S. Rajbman	1980
	Cold rolling		Compensation of periodic disturbances at winding flat material	M. Schneider	1998
			A new control system for a reversing cold mill	T. Ishibashi, T. Kawabata, and T. Ooi	1992
			Reasonable structure of interstrand tension regulator for tandem cold mill	Z.C. Wang, C.Y. Liu, and L. Wei	1992

			Microprocessor based rolling mill digital speed control	P. Boucher and J. Fromont	1980
			The renovation and automation of a tandem cold rolling mill	H.J. ter Maat	1980
Artificial intelligence		Grinding	The intelligent control of an ROM milling circuit	W. Stange and C. McInnes	1995
			Design of the integrated control systems for mineral processing plants	S.-L Jämsä-Jounela	1995
			Self-optimizing control system with knowledge base for the 5.5×1.8 wet autogenous grinding mill	Yu Pingzhang and Wang Jian	1992
			An expert system for control of a SAG/ball mill circuit	S.H. Bradford	1991
		Conditioning	Expert system for coal blending	E. Nakata, H. Fujimoto, and K. Terazono	1991
			Self organizing control of pH in a stirred tank reactor	I.M. Shah and R.K. Rajamani	1991
		Flotation	Supervisor fuzzy controller of a flotation process	M.T. Carvalho and F.O. Durão	2000
			Control strategy for Salvador concentrator flotation columns	L.G. Bergh, J.B. Yianatos, C.A. Acuña, F. López, and H. Pérez	1998
			Machine learning strategies for control of flotation plants	C. Aldrich, D.W. Moolman, F.S. Gouws, and G.F. Schmitz	1995
		Filtration	Modelling module of the intelligent control system for the variable volume pressure filter	S.-L. Jämsä-Jounela, S.J. Toth, M. Oja, and K. Junkkarinen	1998
		Drying	Advanced control of a rotary dryer	L. Yliniemi, J. Koskinen, and K. Leiviskä	1998
			Ore type based expert system for Hitura concentrator	S. Laine	1995
	Hydrometallurgy		Expert system adviser for operators of a Zink Leaching Plant	D. Laguitton, M. Bilodeau, C. Ghibu, J.P. Boulanger, I. Farner, and D. Dupuis	1989
	Furnaces		Blast furnace process control	I. Kostial, P. Nemcovsky, M. Rogal, J. Terpák, L. Dorcák, and I. Petrás	2000
			Sintering machine burn-through management by fuzzy speed control	P. Myllymäki and J. Puotiainen	2000
			Fuzzy control of zinc roaster furnace temperature	T. Rauma, J. Nyberg, and J. Herronen	2000
			Improving EAF energy utilization with electrode controllers based on neural networks	R. Sesselmann	1998
			Application of neural network to supervisory control of reheating furnace in steel industry	Youn Il Kim, Ki Cheol Moon, Byoung Sam Kang, Chonghun Han, and Kun Soo Chang	1997
			Intelligent compound control of direct current electric arc furnace	Xianwem Gao, Shujiang Li, Tianyou Chai, and Xiaogang Wang	1997
			Neural network techniques and its applications in ladle furnace burden	Shujiang Li, Xianwen Gao, Tianyou Chai, and Xiaogang Wang	1997
			Towards a computer-aided training tool for steel making applied to DC-electric arc furnaces	S. Perreard, K. Szafnicki, P. Beaune, and M. Genoud	1995
			Guide to the operation of slag-making in Bof using expert system	A.Z. Pei and Z.-M Cao	1992
			An expert system to aid operation of blast furnace	T.H. Choi, S.H. Yi, I.O. Lee, H.G. Lee, and J.G. Jin	1991
			Application of fuzzy theory for automatic control of hot stove combustion gas flow rate	Y. Maki, Y. Masuda, T. Sawada, T. Matsumoto, H. Obata, and N. Takashima	1989
			Application of expert system to blast furnace operation	S. Watanabe, S. Amano, T. Takarabe, T. Nakamori, H. Oda, M. Taira, and T. Seki	1989

Table 2 (continued)

			Title	Authors	Year
Artificial intelligence	Ox. steelmaking and cont. casting		Breakout prediction of continuous slab casting based on neural networks and fuzzy neural networks	G. Luo and X. Yang	2000
			Application of neural networks to process control in steel industry	M. Jansen, E. Broese, B. Feldkeller, O. Gramckow, T. Poppe, M. Schlang, and G. Sörgel	1998
			Mold level control in continuous caster via nonlinear control technique	YeongSeob Kueon and Seung-Yeol Yoo	1997
			Fuzzy-guided mould level control in continuous steel casting	M. Inkinen, P. Lautala, and E. Saarelainen	1995
			Automation expert system for air separation plant	K. Tashiro, T. Terasaki, M. Watabane, and N. Ando	1991
			Application of expert system to real time cold coil transportation control in finishing line	Y. Anabuki, R. Owaki, and H. Sakiyama	1991
			Knowledge-based model of thermal state of metallurgical ladle	M. Hadjiski, K. Spassov, and D. Filev	1991
			A hybrid expert system combined with a mathematical model for Bof process control	T. Yoshida, H. Tottori, K. Sakane, K. Arima, H. Yamane, and M. Kanemoto	1991
			Expert systems for the automatic surface inspection of steel strip	R. Haataja, M. Kerttula, T. Piironen, and T. Laitinen	1991
			An expert system for continuous steel casting using neural networks	A.B. Bulsari, M. Sillanpaa, and H. Saxen	1991
	Hot rolling		Application of neural-network for improving accuracy of roll force model in hot-rolling mill	D. Lee and Y. Lee	2000
			Coil transfer expert systems for a hot strip mill finishing line	M. Hosoda, T. Kuribayashi, F. Hirao, and K. Takenaka	1991
	Cold rolling		A parallel evolutionary algorithm to solve sequencing problems	W. Sihn and T.D. Graupner	2000
			Tandem: An expert system in troubleshooting electrical faults on a cold rolling mill	R. Martinez, P. Tamborena, H. Berkovic, and J. Perez Roig	1989
Fault diagnosis and process monitoring		Flotation	Development of an image analysis based architecture for the automated control of flotation processes	G. Bonifazi, S. Serranti, and F. Volpe	2000
			Analysis of flotation froth appearance by design of experiments	V. Hasu, J. Hätönen, and H. Hyötyniemi	2000
			Vision- and model-based control of flotation	R. Ylinen, M. Molander, and E.-R. Siliämaa	2000
			On-line image analysis to improve industrial flotation plant performance	D.W. Moolman, C. Aldrich, J.S.J. van Deventer, J.J. Eksteen, W.W. Stange, P. Marais, C. Goodall and R.S. Veitch	1995
		Filtration	Fault diagnosis and remote support system for the variable volume pressure filter	S.-L. Jämsä-Jounela, T. Kuitunen, C. Quiroz, and J. Kämpe	2000
		Recycling	On the use of an expert system in facilitating effective technology transfer	G. Metzner	1995
		Classification	Hydrocyclone underflow analysis using videographic techniques	K.R.P. Petersen, C. Aldrich, D.W. Moolman, J.S.J. van Deventer, W.W. Stange, and C. McInnes	1995
	Hydrometallurgy		Expert control and fault diagnosis of the leaching process in zinc hydrometallurgy plant	M. Wu, J.-H. She, M. Nakano and W. Gui	2000

	Electrorefining		Sensor fault detection using second order informations: Application to metal processing	N. Pezzin-Dobrilla, D. Sauter, D. Theilliol and H. Noura	2000
	Furnaces		Fault diagnosis system for the Outokumpu flash smelting process	S.-L. Jämsä-Jounela, E. Vapaavuori, T. Salmi and M. Grönbärj	2000
			Tool for classification of blast furnace wall temperatures	L. Lassus and H. Saxén	1998
			The application of principle component analysis for predicting blast furnace stability	A.G. Taylor	1998
			An expert system for abnormal status diagnosis and operation quide of a blast furnace	T. Yang, S. Yang, G. Zuo, H. Wei, J. Xu, and Y. Zhou	1992
			An expert system for abnormal condition monitor on blast furnace	Q. Wu, D. Ding, N. Zhang, and G. Cheng	1992
			A multi-model cooperative system for predicting Si-content of molten iron on blast furnace	N. Zhang, W. Lin, C. Chen, and Q. Wu	1992
			Condition monitoring of ferroalloy furnaces	P. Borg, J.G. Waalmann, and T. Leidal	1989
			Automated system of stockline surface analysis and control of burden distribution at the blast furnace top	V. Solovyev, A. Grishkova, and Yu. Basalinsky	1989
			New control system of sinter plant at Chiba works	H. Unzaki, K. Miki, H. Sakimura, A. Kato, H. Takashaki, Y. Utsugizaki, B. Takoshima, and S. Tomita	1986
	Ox. steelmaking and cont. casting		Applications of multivariable statistics at Dofasco	M. Dudzic, V. Vaculik, and I. Miletic	2000
			Development of a scheduling expert system for a steelplant	K. Stohl, W. Snopek, Th. Weigert, and Th. Moritz	1991
			Knowledge engineering an expert system to trouble-shoot quality problems in the continuous casting of steel billets	S. Kumar, J.A. Meech, I.V. Samarasekera, and J.K. Brimacombe	1991
	Hot rolling		Monitoring system for roll stand drives using strain gage technology	A. Asch and W. Hohn	1998
			A large scale fault diagnosis system for a hot strip mill	M. Kurki, T. Taipale, P. Korpipää, and E. Ahola	1998
			VAIQ strip—an on-line system for controlling the mechanical properties of hot rolled strip	J. Andorfer, D. Auzinger, M. Hirsch, G. Hubmer, and R. Pichler	1998
			The diagnostic system for automatic gauge control in hot strip mill	Y. Wakamiya, I. Nitta, K. Yano, T. Itoh, and H. Matsuda	1998
			Advanced strategies for the controlled cooling of steel	P.M. Stone and M.H. Littlejohn	1992
Quality monitoring		Grinding	Optimization of cement manufacturing process	G. Nakamura, T. Aizawa, and K. Nakase	1986
		Filtration	Cemixan on-line analysing and control system for dry powder mixing	K.-E. Nyman	1983
	Furnaces		The quality control system of sintering plant at Kashima steel works	O. Arai, A. Yamamoto, T. Yoko, K. Inada, and S. Yomoto	1983
	Ox. steelmaking nad cont. casting		On-line surface inspection of pickled steel sheet	A.H. Castillejos, F.A. Acosta, M.A. Pedroza, and E. Ruiz	2000
			Neural network model for recognition of characters stenciled on slabs	K. Asano, J. Tateno, S. Maruyama, K. Arai, M. Ibaragi, and M. Shibata	1991
			Automatic flaw inspection and conditioning system of steel billets	T. Iwanaga, K. Mishina, M. Azuma, and T. Tada	1986

Table 2 (continued)

		Title	Authors	Year
		On-line real time surface inspection system for a tin coating line	C. J. Thijs	1986
	Hot rolling	Computer control for continuous casting	K. Miki	1983
		Computer control system of NKK's new seamless tube mill	N. Fushimi, I. Takahashi, M. Saito, T. Kataoka, and S. Kawabata	1986
Others	Hot rolling	The use of a Grafcet model for sequential supervisory control of a multipass experimental rolling mill	D.A. Linkens and Muhammed Ibrahim	1997
		Applying knowledge-based techniques to the scheduling of steel rolling	O. Lassila, P. Mattile, L. Pesonen, M. Syrjanen, and S. Torma	1991
		Expert system for manufacturing order determination in hot-rolling process	H. Fujimoto, S. Arai, K. Sanou, and N. Fukaya	1991

loop strategy for a semiautogenous grinding mill circuit in which Kalman filter estimates of ball and rock holdup in the mill are monitored by the operators. The second was an optimal feedback control strategy to maintain at set point the slurry volume in the sump and the product particle size of a rod/ball mill grinding circuit. The third example is a feedforward strategy in which a Kalman filter estimates the ore floatability in the first two cells of a flotation circuit. The optimal set point values of the collector, frother and pulp level can be found by minimising an economic objective function involving recovery and grade. This research group has implemented the concept very successfully in many plants.

In 1991, a special workshop on expert systems in mineral and metal processing was organised by IFAC. At that time, only two industrial expert system applications were reported in the field of mineral processing: an expert system for coal blending by Nakata, Fujimoto, and Terazono (1992), and an expert system for the control of a SAG/ball mill circuit by Bradford (1992).

In the MMM symposium in 1995, two interesting contributions were published by Aldrich, Moolman, Gouws, and Schmitz (1995): machine learning and on-line image analysis based strategies for the control of flotation. These two papers were the first ones at the IFAC events in this still very active and promising research area. In this IFAC'MM 2000 workshop, three application papers from this area are presented by Bonifazi, Serranti, and Volpe (2000), Hasu, Hätönen, and Hyötyniemi (2000) and Ylinen, Miettunen, Molander, and Siliämaa (2000).

In recent years, the industrial applications of expert systems have largely been concerned with monitoring activities. A feed type expert system for concentrator was presented by Laine (1995). The essential feature of this expert system is the classification of different feed types and their distinct control strategies at the plant. In addition to the classification, the expert system has a database containing information about how to handle the determined feed type. This self-learning database scans historical process data and suggests the best treatment for the ore type under processing. The system was reported to have been tested in two concentrators. A commercial product has recently been installed in a number of real industrial processes (Jämsä-Jounela, Laine, & Ruokonen, 1998).

The first Model Predictive Control (MPC) implementation in flotation control was presented by Suichies, Leroux, Dechert, and Trusiak (1998). The industrial application of model predictive control has been largely confined to petrochemical processes. The broader extension of its exploitation has also been limited in the MMM industries. Among the possible reasons for this are a lack of precedent applications, high engineering costs and inappropriate control technologies.

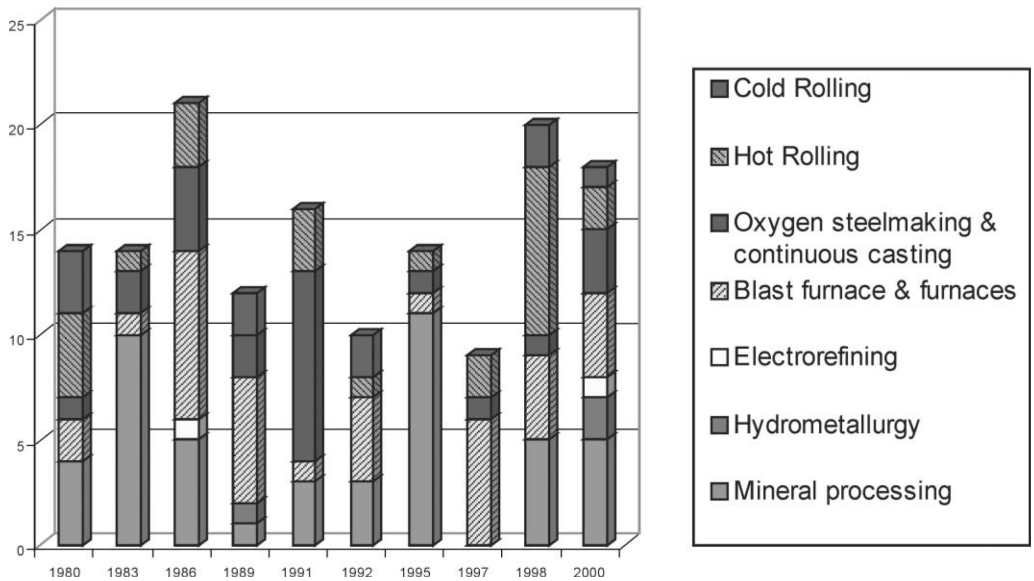

Fig. 1. Number of industrial applications published over the years in the IFAC MMM events.

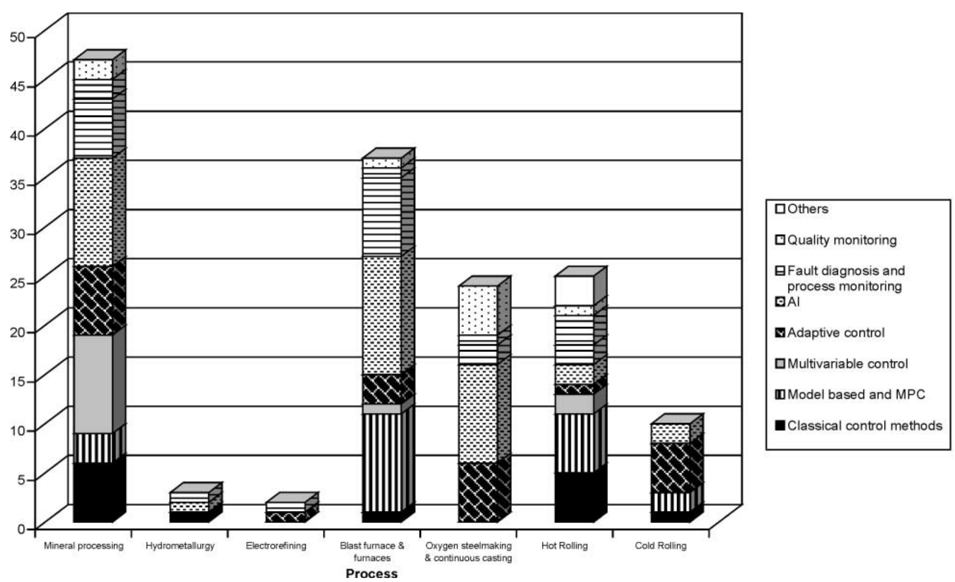

Fig. 2. Distribution of the different control methods according to the kind of process.

4.2. Blast furnace and furnaces

AI methods are applied the most for blast furnace and furnaces although process monitoring and fault diagnosis and model-based control methods play an important role.

Expert systems for blast furnaces are advisory systems constructed to support the operation of the furnace. The system monitors the heat level of the furnace, the position and shape of the cohesive zone and forecasts abnormal conditions in the furnace such as slipping, channelling, sliding and scaffolding. When the abnormalities in the furnace state are detected, the system suggests suitable controlling actions to the process operators.

The first expert system application to blast furnace operation was presented as early as in 1989 by Watanabe et al., 1989. This system was implemented in the Kimitsu Works of Nippon Steel Corporation. This was followed by the implementations in the POSCO No. 3 blast furnace, Korea (Choi, Yi, Lee, Lee, & Jin, 1992), and on an iron and steel plant in China (Wu & Gu, 1992). All the papers reported successful results.

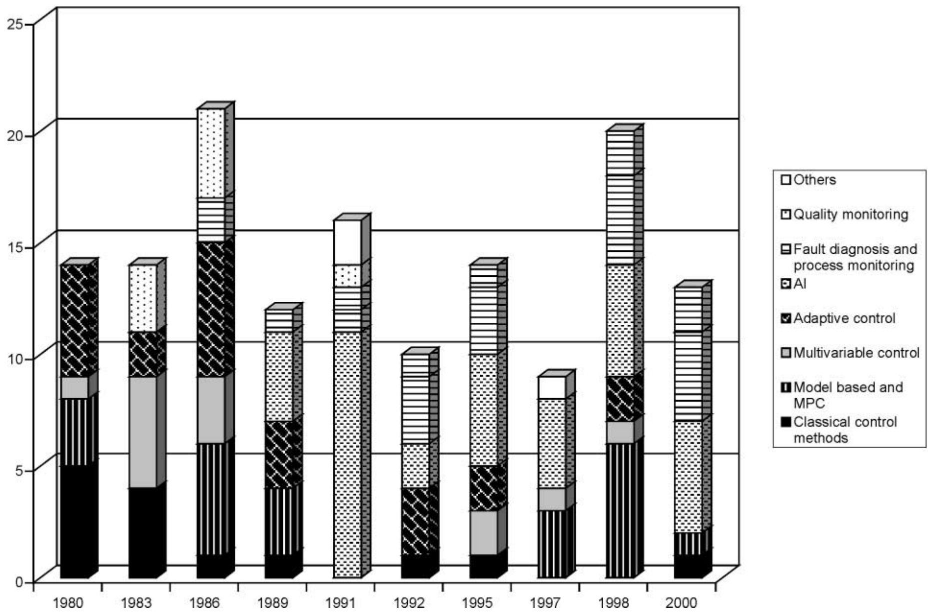

Fig. 3. Distribution of implementations according to the kind of control or supervision methods.

Table 3
Distribution of the different control methods according to the kind of process

	Mineral processing	Hydro-metallurgy	Electro-refining	Blast furnace and furnaces	Steelmaking and continuous casting	Hot rolling	Cold rolling
Classical control methods	6	1	0	1	0	5	1
Model based and MPC	3	0	0	10	0	6	2
Multivariable control	10	0	0	1	0	2	0
Adaptive control	7	0	1	3	6	1	5
AI	11	1	0	12	10	2	2
Fault diagnosis and process monitoring	8	1	1	9	3	5	0
Quality monitoring	2	0	0	1	5	1	0
Others	0	0	0	0	0	3	0
Total	47	3	2	37	24	25	10

Many contributions concerning applied control theory to sinter plant control have been presented in the IFAC MMM events over the years. In the paper "Mathematical approach for the optimization of the sintering process operation", Tamura, Konishi, Morita, Kitayama, and Ohsuzu (1987) describe a model for the operational guidance system for a sintering process, in particular, the components for the heat pattern and the mathematical programming needed to determine the appropriate operational conditions. The method was successfully introduced into the process control system for the Kobe No. 2 sintering plant of Kobe Steel, Japan. The paper "A self-tuning multivariable predictor and its application to the control of sinter quality", by Rose and Kanjila (1987), reports the application of a multivariable predictor for the strength index and the FeO content of the sinter product in an iron ore sintering process. Myllymäki and Poutiainen (2000) describe sintering machine burn-through management by fuzzy speed control at the sintering plant of Rautaruukki Steel, Finland.

A successful fuzzy control of furnace temperature in a zinc roaster at the Kokkola Zinc plant, Finland is reported by Rauma, Nyberg, and Herronen (2000). The controller was put into operation in 1994, and has been in daily use since then.

The application of neural network to the supervisory control of a reheating furnace in the steel industry, by Kim and Kwon (1997), reports on the success in developing and implementing an HME network (a hierarchy of expert nets and gating nets) on-line for the supervisory control of the reheating furnace of the wire rod mill plants at POSCO.

The paper by Ingason and Jonsson (1997), "Control of the silicon ratio in ferrosilicon production" provides a very good example of online implementation of generalised predictive control. One feature of the paper is the realism used in applying the method and the results, as reported by Rose (1998).

4.3. Oxygen steelmaking and continuous casting

In the steel making industries, mould level control plays an important role mainly due to its direct effect on quality and its resulting economic impact. Various kinds of control methods have been applied and reported in IFAC MMM events. Inkinen, Lautala, and Saarelainen (1995) describe the structure, operating strategy and control results with the fuzzy-guided mould level control. The controller was commissioned for Imatra Steel Ab's steel plant at Imatra, Finland.

The paper "Mould level control in continuous caster via nonlinear control technique", by Kueon and Yoo (1997), reports the successful implementation of the sliding mode controller in a continuous caster of the POSCO #2 continuous steel casting process.

4.4. Hot rolling

Owing to the strong interactions between the process variables, hot rolling has been a good candidate for multivariable control. Many successful implementations have been reported, the latest being "Observer-based multivariable control of rolling mills" by Hoshino and Kimura (1998) and the paper by Okata et al. (1997), "Optimal control system for hot-strip finishing mill". The design of a local autonomous control system based on model decoupling and optimal control theory is presented. The experimental results show an improved control of strip thickness, strip tension and looper angle. An application of the local autonomous control system to width control is discussed.

A predictive feedforward control which estimates the local thickness and temperature deviation using a Kalman filter is proposed by Frank, Pichler, Schoiss-wohl, and Staufer (1998). The model-based predictive feedforward control has been applied to finish delivery temperature control by Tonami et al. (1998).

Neural computation has found many successful implementations in rolling. In this workshop, Schlang et al. (2000) report that since 1993 Siemens has been able to gather wide experience in exploiting the advantages of neural networks for process automation in over 40 rolling mills worldwide. The applications are described in more detail in their paper "Current status and future development in neural computation in steel processing".

4.5. Hydrometallurgic processes

Despite the great worldwide expansion of hydrometallurgic processes, there are not many, if any, publications on the control of these processes. This topic is discussed in detail in this IFAC'MM 2000 Workshop in the following papers: Process control advance in gold processing by McMullen and Beartup (2000), State of the art in copper hydrometallurgic processes control by Bergh et al. (2000), Expert control and fault diagnosis of the leaching processes in zinc hydrometallurgy plant by Wu, She, Nakano, and Gui (2000), Experience on SX/EW pilot plant automation by Bergh (2000), On-stream analysis in copper SX-EW processes by Hughes and Saloheimo (2000), Dynamic modelling of heap leaching operations by Munoz, Bartlett, and Bazzanella (2000) and Using principal component analysis and self-organizing map to estimate the physical quality of cathode copper by Rantala, Virtanen, Saloheimo, and Jämsä-Jounela (2000). The lack of process knowledge and accurate on-line information has largely contributed to relatively few developments in information and control systems in this field (Bergh 2000). In the near future, it is expected that significant progress will be made, especially in high level control and monitoring applications.

5. Information technology

Today's world is changing rapidly as companies adjust to global economic competition. Information technology (IT) is currently the main mechanism for streamlining business activities, and is now widespread among companies seeking to improve competitiveness. Technological change and organisational restructuring have been found to bring gains in productivity and market share. Current business is undergoing a major paradigm shift, moving from traditional management into a world of agile organisations and processes. An agile corporation should be able to respond rapidly to market changes. Corporations have been developing a number of IT systems to assist with various aspects of the management of on-line business processes.

The global market generates a need for global technical support. Telecommunication technology is providing a large number of opportunities for enhancing the speed and quality of the support process by enabling remote access to equipment. A technician can contact equipment located far away from his office, diagnose the equipment status, and suggest appropriate repairs online. In some cases, they can even intervene directly in the operation. This enables considerable time saving and a reduction in the costs of the technical support process.

6. Environmental control and monitoring

Environmental control is nowadays an important issue for the survival of the process industries. The monitoring of industrial emissions is the first task in pollution control. The reduction of industrial wastes such as waste gas and waste materials are an essential measure for environmental protection. Yield improvements and energy savings are equal to the reduction in industrial waste, and also improve the profit margin of the products. An exact process control is necessary for the better yield and reduction of power consumption. Forecasting of environmental conditions around an industrial area is also important for better pollution control. Pressure for environmental protection is driving the industry to use better, more advanced methods of control and monitoring.

Recycling is a new field that has its own session "Recycling" in the programme of this IFAC'MM 2000 workshop. The current methods and future trends in recycling and its control will be presented and discussed.

7. Conclusion

Industrial automation is undergoing a change that is more rapid than at any other time in its history. As a result of the changes induced by fieldbus and smart instruments, we can expect to see very profound changes in the hardware and operating software. Fieldbus is truly the beginning of a new era in process control—an era of field-distributed control system (FDCS). Process equipment suppliers are moving into the area and providing process control solutions, i.e. control methods embedded in smart equipment, because of the competitive advantage it brings.

The implementation of advanced technology and the timely use of information have the potential to optimise overall company productivity and, furthermore, to reduce costs under variable processing and economic conditions. This capability will be a key and essential component of the companies that remain competitive in the 21st century. The emphasis will be on plantwide control, integrated business and production control more than on unit process control. Telecommunication technology will provide a larger number of opportunities for enhancing the speed and quality of the support process by enabling remote access to the equipment, process automation and plant information system.

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